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INVESTIGATING THE EFFECTS OF MATHEMATICAL MUSIC ON EEG BRAINWAVE FREQUENCIES*

MATEMATİKSEL MÜZİĞİN EEG BEYİN DALGA FREKANSLARI ÜZERİNDEKİ ETKİLERİNİN ARAŞTIRILMASI

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Abstract

This study aims to present an innovative approach to the music composition process by applying mathematical principles. Five musical pieces were composed using mathematical techniques such as the Golden Ratio and Fibonacci sequences, and the potential applications of these techniques in the field of music therapy were examined. The compositions were played for healthy volunteers, and their neurological and emotional responses were measured using EEG tests. The results of these tests were systematically analyzed through brainwave measurements, allowing for the identification of new techniques and methods for potential use in music therapy. The findings highlight the therapeutic potential of music based on mathematical foundations and contribute to a deeper understanding of the relationship between music and mathematics. This study seeks to fill existing gaps in the literature by integrating mathematical methods into the music composition process and enhancing the effectiveness of music therapy.

Keywords: EEG, Fibonacci numbers, golden ratio, music therapy.

Öz

Bu çalışmanın amacı, müzik besteleme sürecine matematiksel ilkeler uygulayarak yenilikçi bir yaklaşım sunmaktır. Beş müzik eseri, Altın Oran ve Fibonacci dizileri gibi matematiksel teknikler kullanılarak bestelenmiş ve bu tekniklerin müzik terapisi alanındaki potansiyel uygulamaları incelenmiştir. Besteler, sağlıklı gönüllülere dinletilmiş ve EEG testleri yoluyla nörolojik ve duygusal tepkileri ölçülmüştür. EEG test sonuçları, beyin dalgası ölçümleriyle sistematik olarak analiz edilmiş ve bu analizler, müzik terapisinde kullanılabilecek yeni teknikler ve yöntemlerin belirlenmesine olanak sağlamıştır. Çalışmanın bulguları, matematiksel temellere dayalı müziklerin terapötik potansiyelini ortaya koymakta ve müzik ile matematik arasındaki ilişkiyi daha derinlemesine anlamamıza katkıda bulunmaktadır. Bu çalışma, mevcut literatürdeki boşlukları doldurmayı amaçlamakta olup, müzik besteleme sürecine matematiksel yöntemlerin entegrasyonuyla müzik terapisinin etkinliğini artırmayı hedeflemektedir.

Anahtar Kelimeler: EEG, Fibonacci sayıları, altın oran, müzik terapi.

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1. INTRODUCTION

Music and mathematics share a profound connection, with mathematical principles being integral to music theory and prompting further exploration. Historically, mathematics has significantly influenced the structural framework of music, illustrating its impact and potential for devising new sound systems based on mathematical ratios (Panti, 2020). For instance, Pythagoras elucidated the harmonious relationships between note frequencies, leading to the Pythagorean tuning system (Nyhoff, 2024). Similarly, Bach explored the mathematical dimensions of instrument tuning (Siddharthan, 1999; Lindley & Ordgies, 2006).

The psychological impact of music is a captivating subject that continues to attract substantial research interest. Researchers often employ music, particularly classical compositions, as stimuli to investigate its effects (Okay & Ece, 2019; Canyakan, 2020). Studies have demonstrated that music significantly influences various physiological responses, including changes in blood oxygen saturation, heart rate, and respiration, especially in infants (Cassidy & Stanley, 1995). Leonard Meyer's seminal work, "Emotion and Meaning in Music," emphasizes the intricate relationship between music and psychology (Spitzer, 2009).

Music therapy has a longstanding history, with early mentions found in the writings of Plato, who advocated for the inclusion of music in education for holistic development (Plato, 2006). Islamic scholars, such as Farabi, also acknowledged the impact of musical notes on emotional states (Yılmaz et al., 2019). Throughout the Seljuk and Ottoman periods, music therapy was employed as a complementary treatment in bimarhanes (mental hospitals) and darüşşifas (hospitals), and its practice has now expanded globally (Sufie & Sidik, 2017). Moreover, the novel sound system developed in this paper holds the potential to contribute to the existing literature on music therapy.

The electrical activity of the brain is measured using the EEG (Electroencephalography) testing method (Medicalpark, 2024). The psychological assessment for the project was conducted using this method, following ethical committee approval. Brain waves, which are crucial for our project, can be obtained through this test. They are categorized based on their frequency and carry different meanings. Delta waves, with frequencies up to 3Hz, are observed during deep sleep. Theta waves, ranging from 4Hz to 7Hz, occur during drowsiness, deep thinking, and meditation. Alpha waves, with frequencies between 8Hz and 12Hz, are present during wakefulness. Beta waves, ranging from 13Hz to 30Hz, are associated with focused thinking and concentration. Gamma waves, with frequencies above 30Hz, are important for learning and memory (Teplan, 2002; Koudelková et al., 2018).

Given the distinct characteristics and implications of alpha, beta, delta, gamma, and theta waves, they will play a central role in analyzing the music compositions created in our project. For instance, the relaxation associated with alpha waves, as well as the logical and analytical thinking linked to beta waves, can provide valuable insights for the examination of music compositions (Koudelková et al., 2018).

Mathematical structures are extensively used in music, serving as a foundation for various musical compositions. J.S. Bach's works, for example, exhibit structural and artistic features that can be analyzed and divided into distinct musical pieces, such as "prelude" and "recitative." This approach reveals the significant utilization of mathematics in music, including the exploration of values converging toward the golden ratio (Mutver, 2007). In addition to Bach's works, studies have investigated the mathematical and musical harmonies in different pieces of music. Frequency tables have been constructed, showcasing the mathematical and musical relationships between various measures. These studies have consistently demonstrated the use of the golden ratio across different sections of music, providing further evidence of Bach's extensive application of mathematics (Mutver, 2007).

Despite these endeavors, the relationship between mathematics and music remains a subject of ongoing debate, and its full elucidation has yet to be achieved. In light of this, our project aims to examine this relationship objectively by relying on medical and scientific data, thus contributing to a deeper understanding of the subject.

In this study, music has been designed using mathematical structures such as Fibonacci sequences and the Golden Ratio. To facilitate a systematic analysis of the music, the use of an EEG (Electroencephalography) device has been decided. The generated music will be played for subjects, and during this process, brainwave data will be collected through the EEG device. The collected data will be analyzed and interpreted in light of the mathematical properties of alpha, beta, delta, gamma, and theta waves. This approach aims to examine how the mathematical structures of music interact with brain activity and their effects on neurological responses.

2. METHOD

In this paper, three pieces of music were created using the Fibonacci sequence and the Golden Ratio by consulting the full-text project named "Effects of Musics Composed Using Mathematical Methods and DNA On the EEG Frequency Bands of Healthy Individuals". The classical music piece "Grieg: Peer Gynt Suite No. 1, Morning Mood" was used for comparison with the Golden Ratio music composed in this project.

2.1. Creating Music with Mathematical Structures

In this study, the process of musical composition was restructured through the application of mathematical frameworks. Specifically, the Fibonacci sequence and the Golden Ratio were employed to determine the distribution and frequencies of musical notes.

The first method involved mapping the Fibonacci sequence, modulo 7, onto musical notes. This approach translated the inherent mathematical order of the Fibonacci series into a musical form. An algorithm developed using Python automatically generates a music file based on a user-defined number of Fibonacci numbers.

The second method was based on Zeckendorf's Theorem, which states that every positive integer can be uniquely represented as the sum of non-consecutive Fibonacci numbers. This principle was utilized in the creation of musical compositions. Selected

Fibonacci numbers were mapped to musical notes, ensuring a balanced distribution within the composition.

The third method involved the application of the Golden Ratio to musical frequencies. The traditional Pythagorean Diatonic Scale was redesigned using the Golden Ratio, resulting in a novel frequency structure derived from this mathematical constant. Considering the limited existing literature on the integration of the Golden Ratio into music theory, this scale was optimized for mathematical harmony.

The methods used in the creation of music can be categorized into three main approaches:

2.1.1. First Method

This approach involves calculating the remainder of each element in the Fibonacci Number Sequence when divided by 7 (mod 7 operation). Each resulting number is then paired with a corresponding musical note. This method allows for the selection of the desired number of Fibonacci numbers and the subsequent generation of a music file. The corresponding algorithm has been implemented in Python code, allowing for the determinaton of the number of Fibonacci numbers to be processed and the generation of a music file accordingly

2.1.2. Second Method

This approach is based on Zeckendorf's Theorem, which states that every positive integer can be expressed as the sum of one or more Fibonacci numbers. In this case, a specific Fibonacci number (e.g., 34) is chosen, and it is represented as the sum of various Fibonacci numbers. Each resulting number is then assigned to different musical notes through a cyclical process, ensuring equal representation of all notes. This cyclical process ensures that all notes are equally represented. An example composition generated by this method is provided in Figure 1. Similarly to the first method, a Python code is created and the cyclical process is implemented in Python.

Figure 1. The Music Composition Example Generated Through the Method Based on Dividing Fibonacci Numbers According to the Zeckendorf Theorem

2.1.3. Properties of Fibonacci Sequence Music

The properties of the Fibonacci sequence music are summarized in the following table:

Table 1. Correspondence of Note Frequencies and Fibonacci Numbers for the First Period in Music based on the Zeckendorf Theorem.

Note	Count in the First Period	Fibonacci Number
Do	1	F_1
Re	5	F_5
Mi	5	F_5
Fa	8	F_6
Sol	5	F_5
La	5	F_5
Si	5	F_5
Total	34	F_9

Table 1 contains the numbers corresponding to the notes in 'Figure 1,' while Table 2 presents the distances between the notes. The red vertical line in 'Figure 1' indicates the end of the first period, with subsequent periods shifting the notes by one digit.

Table 2. Correspondence of Intervals between Notes and Fibonacci Numbers for the First Period, on a Note-by-Note Basis

Note	Distances Between Consecutive Notes	Distances Between Consecutive Notes as Fibonacci Numbers
Do	-	-
Re	3 – 3 – 13	$F_4 - F_4 - F_7$
Mi	3 – 3 – 5 – 5	$F_4 - F_4 - F_5 - F_5$
Fa	3 – 5 – 3 – 3 – 5 – 5 – 0	$F_4 - F_5 - F_4 - F_4 - F_5 - F_5 - F_0$
Sol	3 – 3 – 3 – 3 – 3	$F_4 - F_4 - F_4 - F_4 - F_4$
La	3 – 8 – 3 – 5	$F_4 - F_6 - F_4 - F_5$
Si	8 – 2 – 2 – 2	$F_6 - F_3 - F_3 - F_3$

2.1.4. Third Method

The Golden Ratio, approximately 1,618 (often denoted by the Greek letter phi, ϕ), is an irrational number found throughout nature, art, and mathematics. It's defined when a line is divided into two parts, and the ratio of the whole line to the longer part is equal to the ratio of the longer part to the shorter part. It's often associated with aesthetic appeal and harmonious proportions. The third music was composed by manipulating the Pythagorean Diatonic Scale. In this context, the formula of the Pythagorean Diatonic Scale that is equal to $(\frac{3}{2})^n$ changed with the ϕ^n. As a result, new frequencies were obtained by using the Golden Ratio. The ratios and the frequencies of the scale is given in Table 6 and Table 7.

On the other hand, the methodology used to compose 3 pieces of music was automized by writing the Python algorithms. The Python algorithms that were used in this paper are given in Code Block 1 and Code Block 2.

In music theory, the following formula is used to compare the frequencies of two notes:

If the first note is denoted as x, and the second note as y;

Distance Between Notes = $8 \log_2(y - x)$

The ratios between consecutive notes in both sequences are presented in Table 7, based on the provided formula.

Table 3. Ratios between Consecutive Notes

Ration Notes	**Do-Re**	**Re-Mi**	**Mi-Fa**	**Fa-Sol**	**Sol-La**	**La-Si**	**Si-Do**
Pythagorean	1,34	1,38	0,58	1,38	1,39	1,31	0,62
Golden Ratio	0,64	0,67	1,14	0,66	0,65	2,45	1,80

Table 4. Frequencies Generated According to the Original Pythagorea

Do	Re	Mi	Fa	Sol	La	Si	Do
260 Hz	292 Hz	329 Hz	346 Hz	390 Hz	440 Hz	493 Hz	520 Hz

Based on the provided ratios in Table 3 under the "Golden Ratio" designation, an approximation of the corresponding musical note frequencies can be extrapolated. This derivation assumes that the listed numerical values represent the multiplicative factor between the frequencies of consecutive notes within a musical scale. Utilizing the frequency of Do (260 Hz) from the accompanying frequency table as the initial reference point, the subsequent frequencies are estimated as follows:

Do: 260 Hz (reference frequency)

Re: Frequency of Do multiplied by the Do-Re ratio
(260 Hz×0,64=166,4 Hz)

Mi: Frequency of Re multiplied by the Re-Mi ratio
(166,4 Hz×0,67=111,49 Hz)

Fa: Frequency of Mi multiplied by the Mi-Fa ratio
(111,49 Hz×1,14=127,10 Hz)

Sol: Frequency of Fa multiplied by the Fa-Sol ratio
(127,10 Hz×0,66=83,89 Hz)

La: Frequency of Sol multiplied by the Sol-La ratio
(83,89 Hz×0,65=54,53 Hz)

Si: Frequency of La multiplied by the La-Si ratio
(54,53 Hz×2,45=133,59 Hz)

Do (octave): Frequency of Si multiplied by the Si-Do ratio
(133,59 Hz×1,80=240,46 Hz

Table 5. Frequencies Generated According to the Golden Ratio

Do	Re	Mi	Fa	Sol	La	Si	Do
260 Hz	166 Hz	111 Hz	127 Hz	83 Hz	54 Hz	133 Hz	240 Hz

In order to ensure harmony between the frequency values of the notes in the mathematical music to be created, it is not appropriate to change the "3/2" ratio too much. At this point, it is seen that the golden ratio does not disrupt the harmony between the note frequencies due to its numerical value.

2.1.5. Modification of the Pythagorean Diatonic Scale for 12 Notes

This study can be applied to the twelve-tone equal temperament system.The Pythagorean Diatonic Scale plays a crucial role in modern frequency generation, and thus studying the Pythagorean sequence is important. However, there is a lack of exploration regarding redesigning the Pythagorean sequence using the golden ratio. The current method utilizes (3/2)^n as the basis for constructing the Pythagorean sequence and obtaining frequencies. The original ratios and frequencies of the Pythagorean sequence are presented in Tables 6 and 7, respectively

Table 6. Frequencies Generated According to the Golden Ratio

Do	Do#	Re	Re#	Mi	Fa	Fa#	Sol	Sol#	La	La#	Si
1,00	1,05	1,12	1,18	1,25	1,30	1,38	1,46	1,55	1,61	1,71	1,81

Table 7. The Frequencies of the Newly Constructed Phytagorean Scale by Golden Ratio

Do	Do#	Re	Re#	Mi	Fa	Fa#	Sol	Sol#	La	La#	Si
271,9	288,0	304,9	322,9	342,0	356,0	376,9	399,2	422,7	440,0	465,9	493,4

2.2. Conversion of Music into Audio Files

To perform the playback of music compositions created using mathematical structures, software methods were employed. A software was developed using the Music21 library in Python, resulting in the generation of '.mp3' audio files. The project attachments provide access to these audio files

Studies were carried out under the supervision of Assoc. Prof. Dr. Mustafa Kemal KARAOSMANOĞLU and Prof. Dr. Arda Eden, who are listed in the "Acknowledgements" section, in order to improve the notation of the music and increase its reliability.

2.3. Electroencephalography (EEG) Test Methods and Analysis Techniques

In this study, music was created using mathematical structures. This study aims to analyze the changes in brainwave activity of healthy individuals in response to music composed using mathematical principles. At this point, a systematic analysis of these musical compositions is necessary. To facilitate a systematic analysis, the use of an Electroencephalography (EEG) device was decided upon. it is known by researchers that factors such as the number of volunteers and the duration of listening to music are important for the EEG test method, which has a wide area of use in the health field and is a test method, to provide objective data to the research. Electroencephalography (EEG) tests employed in the study were conducted in the EEG recording room of Erenköy Psychiatry Hospital, following approval from the ethics committee (Decision No: 25, Date: March 31, 2023). The participant group consisted of 12 healthy individuals (8 males, 4 females) aged over 18 years with a minimum of a high school diploma The study was conducted in the EEG recording room at Erenköy Psychiatric Hospital, with ethical approval obtained from the institution's ethics committee and the EEG Test process have been taken at the Erenköy Psychiatric Hospital.

During the experimental procedure, participants listened to designated musical pieces in a quiet environment while their brainwave activities were recorded using an EEG device. Prior to the music listening session, a 'music-absent' baseline measurement was taken to evaluate the participants' neurological status. The music listening process comprised five distinct phases, with each phase structured into two-minute segments.

In the data analysis phase, delta, gamma, and theta wave activities, with a primary focus on alpha and beta waves, were evaluated in detail. Brain topography maps were generated to visualize the cognitive and emotional effects of the music on the participants. A decrease in beta waves (associated with stress and arousal) and an increase in alpha waves (associated with relaxation and focus) were considered significant indicators for understanding the therapeutic potential of mathematical music.

The objective is to have all the generated music compositions listened to by individuals and, during this process, collect brainwave data through the EEG device. The music compositions are analyzed using the EEG testing method, the brain waves namely alpha and beta waves were essential for this process The collected data will then be analyzed and interpreted in light of the characteristics of alpha, beta, delta, gamma, and theta waves, as explained in the introduction section. In the data analysis phase, brain topography maps were central. Beta waves, symbolized by red color, implying emotional states such as stress and action, are expected to be transformed into blue regions through the designed mathematical music.

Appendix 1 shows the brain topographical mapping images for all individuals and for all tried hypothesis. The occurred red areas imply a more beta-oriented brain state, while blue areas imply a more alpha-oriented brain state.

At the end of the composing process, the four pieces of music were examined by analyzing the 12 healthy individuals' EEG test results that were made by looking at their Brain Topographical Maps. The participant sample consisted of healthy individuals over the age of 18, including 8 males and 4 females, all with at least a high school diploma. The experimental procedure involved playing pre-designed musical sequences to participants in a fixed order, within an environment free from external noise and stimuli. Prior to the musical presentations, a "music-free recording" was conducted to establish a baseline of brainwave activity. Classical music was played during this baseline phase and served as a control. The playback sequence commenced with the "music-free period," followed by presentations of Fibonacci1, Fibonacci2, sequence-influenced music, golden ratio music, and finally, classical music. Each phase was structured into two-minute segments. The analyses were conducted under the supervision of neurology specialists at the hospital."

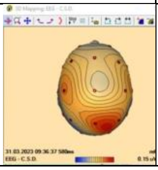
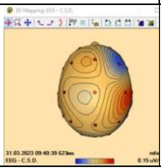
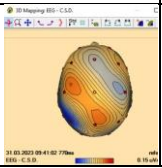
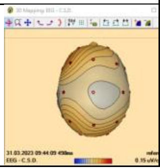
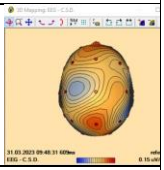
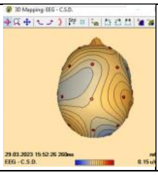
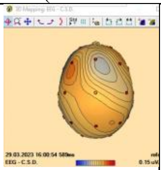
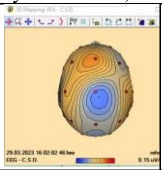
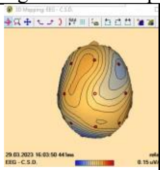
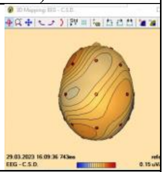
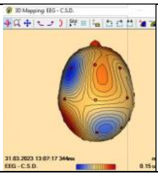
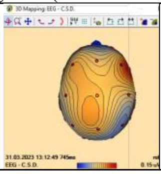
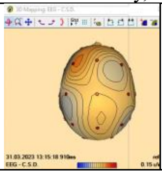
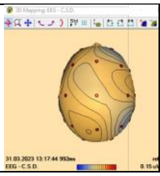
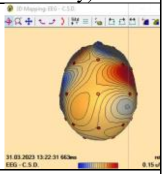
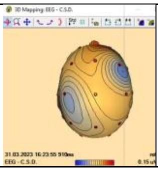
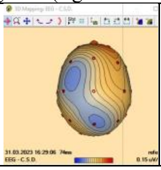
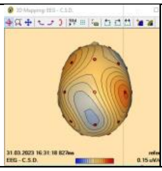
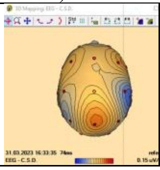
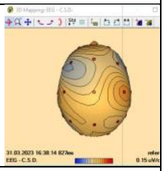
3. RESULTS

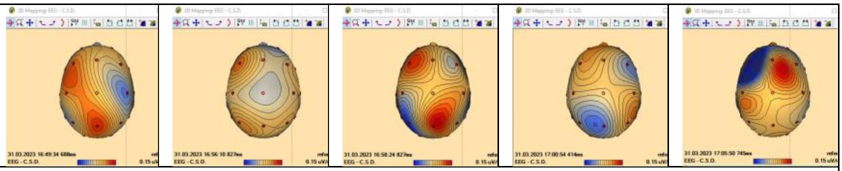
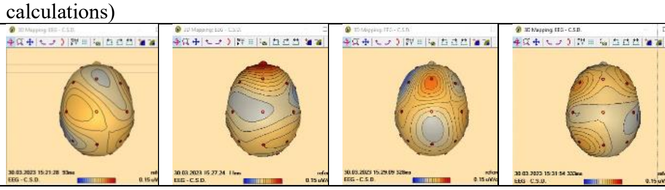
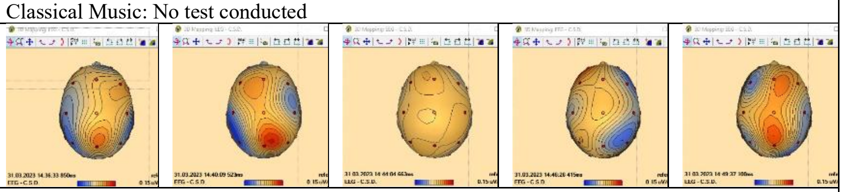
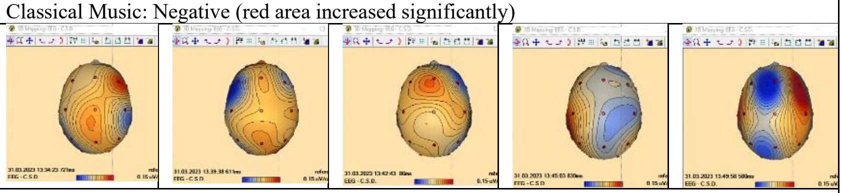
With the given methods, some results thought to be intriguing are found. Table 1 shows the comparisons for the given people (named anonymously) in 4 different categories. The results are given in Table 8 and Table 9.

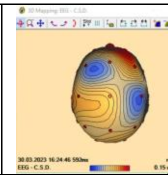
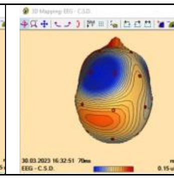
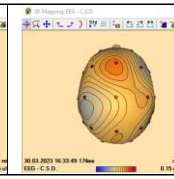
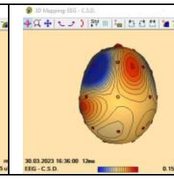
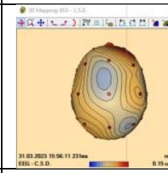
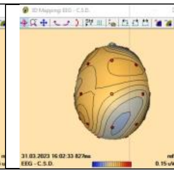
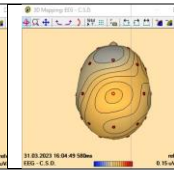
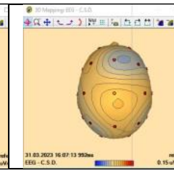
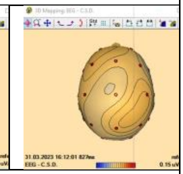
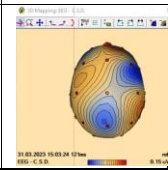
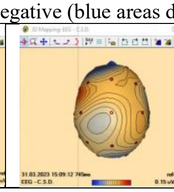
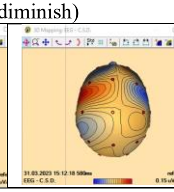
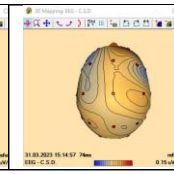
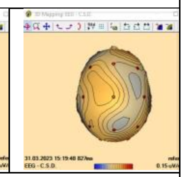
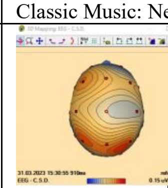
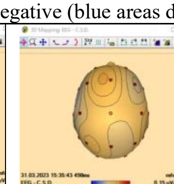
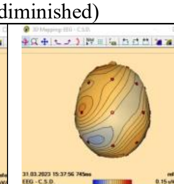
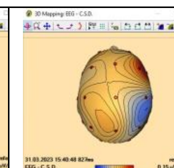
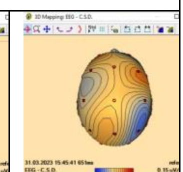
Table 8. EEG Test Result

	Comparison with No-Music State			
Name	Fibonacci 1	Fibonacci 2	Golden R.	Classic
Male 1	+	+	+	+
Male 2	–	+	+/- (Neutral)	–
Male 3	–	+/– (Neutral)	+/– (Neutral)	–
Male 4	+	+/– (Neutral)	–	+/– (Neutral)
Male 5	+	–	+	+/– (Neutral)
Male 6	+/– (Neutral)	+	+/– (Neutral)	Not-Tested
Male 7	+/– (Neutral)	+/– (Neutral)	+	–
Male 8	+	+	+/– (Neutral)	+
Female 1	+	–	–	Not-Tested
Female 2	+/– (Neutral)	+/– (Neutral)	+/– (Neutral)	–
Female 3	–	–	–	–
Female 4	+	+	+	+

Table 9. EEG Test Results by Brain Topographical Maps

	No-Music	Fibonacci 1	Fibonacci 2	Golden Ratio	Classis Music
M 1					
M 1 **RE** **SU** **LT**	Fibonacci 1: Positive (blue area expanded) Fibonacci 2: Positive (blue area expended, red area diminished) Golden Ratio: Positive (red area disappeared) Classic Music: Positive (reddish area stayed the same, although blue area expended)				
M 2					
M 2 **RE** **SU** **LT**	Fibonacci 1: Negative (red area expended) Fibonacci 2: Positive (blue area expended) Golden Ratio: Neutral (no significant change seen) Classic Music: Negative (blueish are declined smoothly, reddish area increased smoothly)				
M 3					
M 3 **RE** **SU** **LT**	Fibonacci 1: Negative (blue areas diminished) Fibonacci 2: Neutral (blue and red areas diminished together) Golden Ratio: Neutral (blue and red areas diminished together) Classic Music: Negative (significant increase in red area is shown)				
M 4					
M 4 **RE** **SU** **LT**	Fibonacci 1: Positive (blue areas increased) Fibonacci 2: Neutral (no significant change reported) Golden Ratio: Negative (red area occurred) Classic Music: Neutral (no significant change reported)				

M 5	
M 5 **RE** **SU** **LT**	Fibonacci 1: Positive (red area disappeared) Fibonacci 2: Negative (red area increased significantly) Golden Ratio: Positive (blue are expanded) Classic Music: Neutral (blue are moved to the eye region, where we don't take in our calculations)
M 6	 **No-Test**
M 6 **RE** **SU** **LT**	Fibonacci 1: Neutral (only change is seen in the eye region) Fibonacci 2: Positive (little change in the back and the left side of the head) Golden Ratio: Neutral (no significant change) Classical Music: No test conducted
M 7	
M 7 **RE** **SU** **LT**	Fibonacci 1: Neutral (red and blue areas increased together) Fibonacci 2: Neutral (red and blue areas disappeared together) Golden Ratio: Positive (blue area increased significantly) Classical Music: Negative (red area increased significantly)
M 8	
M 8 **RE** **SU** **LT**	Fibonacci 1: Positive (red are at the back disappeared, some blue regions occurred) Fibonacci 2: Neutral (no significant change seen) Golden Ratio: Positive (blue areas expended very significantly) Classical Music: Positive (blue areas expended very significantly)

F 1					**No-Test**
F 1 **RE SU LT**	Fibonacci 1: Positive (a very significant blue area occurred) Fibonacci 2: Negative (blue areas diminished slightly) Golden Ratio: Negative (red areas appeared) Classic Music: No test conducted				
F 2					
F 2 **RE SU LT**	Fibonacci 1: Neutral (no significant change reported) Fibonacci 2: Neutral (no significant change reported) Golden Ratio: Neutral (no significant change reported) Classic Music: Negative (blue areas diminish)				
F 3					
F 3 **RE SU LT**	Fibonacci 1: Negative (blue areas diminished) Fibonacci 2: Negative (blue areas diminished, while red areas expanded) Golden Ratio: Negative (blue areas diminished) Classic Music: Negative (blue areas diminished)				
F 4					
F 4 **RE SU LT**	Fibonacci 1: Positive (red areas diminished) Fibonacci 2: Positive (red areas diminished, while blue areas expended) Golden Ratio: Positive (blue areas expanded) Classical Music: Positive (blue areas expanded)				

The EEG test results obtained with the given methods reveal several intriguing findings. The analyses summarized in Table 8 and Table 9 highlight the brainwave responses of individuals to different types of music. These responses are discussed below.

Table 10. Distribution of Positive, Neutral, and Negative Responses by Participants and Conditions

Response Type	Fibonacci 1	Fibonacci 2	Golden Ratio	Classic
Positive	Male 1, Male 4, Male 5, Male 8, Female 1, Female 4	Male 1, Male 2, Male 6, Female 4	Male 1, Male 5, Male 7, Female 4	Male 1, Male 8, Female 4
Neutral	Male 6, Male 7, Female 2	Male 3, Male 4, Male 7, Female 2	Male 2, Male 3, Male 6, Male 8, Female 2	Male 4, Male 5,
Negative	Male 2, Male 3, Female 3	Male 5, Female 1, Female 3	Male 4, Female 1, Female 3	Male 2, Male 7, Female 2, Female 3

Table 11. Gender-Based Response Percentages Across Different Music Conditions

Condition	Positive Responses (Male)	Positive Responses (Female)	Neutral Responses (Male)	Neutral Responses (Female)	Negative Responses (Male)	Negative Responses (Female)
Fibonacci 1	50% (4/8)	50% (2/4)	25% (2/8)	25% (1/4)	25% (2/8)	25% (1/4)
Fibonacci 2	50% (4/8)	25% (1/4)	37,5% (3/8)	%25 (1/4)	12,5% (1/8)	50% (2/4)
Golden Ratio	37,5% (3/8)	25% (1/4)	50% (4/8)	25% (1/4)	12,5% (1/8)	50% (2/4)
Classic	28,6% (2/7)	33,3% (1/3)	28,6% (2/7)	33,3% (1/3)	42,9% (3/7)	66,7% (2/3)

Note. In the classical music tests, the test results for Male 6 and Female 1 were not obtaine

4. DISCUSSION

Let's analyze the EEG results in three separate sections: Positive, Neutral, and Negative

4.1. Positive Responses

Fibonacci 1:

Participants: Male 1, Male 4, Male 5, Male 8, Female 1, Female 4

Observation: The positive responses in Fibonacci 1 are distributed across both male and female participants. However, the male participants exhibit a broader range of responses, with Female 1 and Female 4 being the only female participants providing positive feedback in this condition. This suggests that Fibonacci 1 might be perceived more favorably by males in this context.

Fibonacci 2:

Participants: Male 1, Male 6, Male 8, Female 4

Observation: Fibonacci 2 sees a more limited distribution of positive responses, especially when compared to Fibonacci 1. Notably, Female 4 is the only female participant providing a positive response in this condition, which contrasts with the more frequent positive responses from male participants. This might indicate a gender-based difference in how Fibonacci 2 is perceived.

Golden Ratio:

Participants: Male 1, Male 5, Male 7, Female 4

Observation: Golden Ratio yields positive responses predominantly from male participants, with Female 4 being the only female participant providing a positive response. This pattern suggests a stronger tendency for male participants to respond positively to the Golden Ratio condition compared to their female counterparts.

Classic:

Participants: Male 1, Male 8, Female 4

Observation: The distribution of positive responses for Golden Ratio - Classic is similar to the Golden Ratio condition, where only a few participants (Male 1, Male 8, and Female 4) provided positive responses. Again, this suggests that females may have a more restrained reaction in this condition, as only Female 4 provides a positive response.

4.2. Neutral Responses

Fibonacci 1:

Participants: Male 6, Male 7, Female 2

Observation: Neutral responses are relatively evenly distributed across both male and female participants. Female 2 is the only female participant who gives a neutral response in Fibonacci 1, indicating that this condition does not evoke strong positive or negative reactions from the participants.

Fibonacci 2:

Participants: Male 3, Male 4, Male 7, Female 2

Observation: Neutral responses are similarly distributed among male and female participants in Fibonacci 2. This condition shows a relatively balanced response, with Female 2 again showing a neutral stance, which is nearly consistent with the response pattern observed in Fibonacci 1.

Golden Ratio:

Participants: Male 2, Male 3, Male 6, Male 8, Female 2

Observation: The distribution of neutral responses is broader in the Golden Ratio condition, with both male and female participants providing neutral feedback. This suggests that Golden Ratio might be a less polarizing condition than Fibonacci 1 or Fibonacci 2, as it elicits a more mixed set of responses.

Classic:

Participants: Male 4, Male 5

Observation: In the Golden Ratio - Classic condition, neutral responses are overwhelmingly from male participants, with no female participants providing neutral feedback. This indicates a greater tendency for males to respond neutrally in this condition compared to the others.

4.3. Negative Responses

Fibonacci 1:

Participants: Male 2, Male 3, Female 3

Observation: Negative responses in Fibonacci 1 are distributed among both male and female participants, with Female 3 being the only female to provide a negative response in this condition. This could suggest that the Fibonacci 1 condition has a more significant negative impact on certain participants, though the gender distribution is fairly balanced.

Fibonacci 2:

Participants: Male 2, Male 5, Female 3

Observation: Similar to Fibonacci 1, Fibonacci 2 also evokes negative responses from both male and female participants, with Female 3 again being the only female participant to provide a negative response. The higher frequency of male participants giving negative responses could suggest that Fibonacci 2 may be less favorable for male participants compared to the other conditions.

Golden Ratio:

Participants: Male 4, Female 1, Female 3

Observation: The Golden Ratio condition elicits a higher proportion of negative responses from female participants, with both Female 1 and Female 3 giving negative feedback. This could indicate that the Golden Ratio condition is perceived more negatively by female participants compared to male participants, who provided fewer negative responses.

Classic:

Participants: Male 2, Male 7, Female 2, Female 3

Observation: In the Classic condition, both male and female participants provided negative responses. Notably, the inclusion of both female participants (Female 2 and Female 3) in the negative category could indicate that this condition has a particularly strong negative effect on certain individuals, particularly females.

4.4. Overall Observations and Gender-Based Trends

4.4.1. Gender Differences in Responses

There is a noticeable gender-based trend in the positive responses, with male participants more frequently providing positive feedback across most conditions (Fibonacci 1, Fibonacci 2, and Golden Ratio).

Female participants, on the other hand, tend to provide more neutral and negative responses, especially in the Golden Ratio and Classic conditions.

4.4.2. Condition-Based Trends

Fibonacci 1 and Golden Ratio tend to generate more positive responses overall, but there are significant variations in how male and female participants react to these conditions. Males tend to react more positively, while females show more mixed reactions.

Classic elicits more negative feedback, especially from female participants, suggesting that this condition may be perceived unfavorably by them.

4.4.3. Neutral Responses as a Balanced Stance

The neutral responses generally appear across all conditions but are most common in Golden Ratio and Fibonacci 2, where participants seem to lack a strong preference or opinion. This might indicate that these conditions are not as strongly polarizing as others, such as the Classic.

5. CONCLUSION AND FURTHER RESARCH

Traditional music systems are rooted in the Pythagorean diatonic scale. To maintain the desired consonance between note frequencies in mathematical music compositions, it is crucial to avoid significant modifications of the "3/2" ratio. In this context, the numerical value of the golden ratio appears to not disrupt the harmony between note frequencies. Considering the proportional relationships between notes in the newly constructed scale and the golden ratio-based musical system, it is posited that this approach does not negatively impact the harmony of the classical system and may even offer certain potential advantages. This proposition suggests new avenues of exploration for researchers in the context of musical harmony and mathematical relationships.

This analysis suggests that participants' gender plays a significant role in their response patterns across different conditions. Male participants appear to have a more favorable response to Fibonacci 1 and Golden Ratio conditions, while female participants tend to show more neutrality or negativity, particularly in the Classic condition.

The analysis reveals several key insights into how different types of music influence brain activity.

5.1. Fibonacci-Based Music

The Fibonacci-based compositions (Fibonacci 1 and Fibonacci 2) generally elicited positive responses in many participants, particularly in the male group. This suggests that music based on mathematical sequences can have a beneficial effect on brainwave activity, potentially enhancing cognitive functions and emotional states.

5.2. Golden Ratio-Based Music

The Golden Ratio compositions showed a mix of positive and neutral responses, with fewer negative reactions compared to other music types. This indicates that the Golden Ratio may create a harmonious effect on the brain, promoting a state of balance and well-being.

5.3. Classical Music

Classical music, used as a control, elicited varied responses. While some participants experienced positive effects, others showed negative or neutral responses. This variability could be due to individual preferences and familiarity with the music.

5.4. Gender Differences

The results indicate potential gender differences in response to music, with males generally showing more positive responses to Fibonacci-based music, while females displayed more variability in their reactions.

5.5. Topographical Changes

The brain topographical maps highlight the specific regions affected by different music types. Positive responses were often associated with increased blue areas, indicating enhanced brain activity and potentially improved cognitive functions.

In conclusion, the findings suggest that mathematical structures in music, such as the Fibonacci sequence and the Golden Ratio, can positively influence brainwave activity. These insights could inform future research on the therapeutic applications of music and its potential benefits for cognitive and emotional health.

Further research could focus on investigating why these gender-based differences occur, possibly exploring psychological or cultural factors that may influence how individuals perceive and respond to the conditions presented. Additionally, examining the underlying reasons for the higher frequency of neutral and negative responses in certain conditions could provide deeper insights into participant preferences and perceptions.

6. SOFTWARE

In this section, the Python code we created while generating music will be provided

```
from music21 import *
index = 0
a4 = note.Note('A4')
a4.duration = duration.Duration(0.5)
b4 = note.Note('B4')
b4.duration = duration.Duration(0.5)
c4 = note.Note('C4')
c4.duration = duration.Duration(0.5)
d4 = note.Note('D4')
d4.duration = duration.Duration(0.5)
e4 = note.Note('E4')
e4.duration = duration.Duration(0.5)
f4 = note.Note('F4')
f4.duration = duration.Duration(0.5)
g4 = note.Note('G4')
g4.duration = duration.Duration(0.5)

def add_note(note_letter):
    if note_letter == 'a':
        n = note.Note('A4')
        n.duration = duration.Duration(0.5)
```

```
        s.append(n)
    elif note_letter == 'b':
        n = note.Note('B4')
        n.duration = duration.Duration(0.5)
        s.append(n)
    elif note_letter == 'c':
        n = note.Note('C4')
        n.duration = duration.Duration(0.5)
        s.append(n)
    elif note_letter == 'd':
        n = note.Note('D4')
        n.duration = duration.Duration(0.5)
        s.append(n)
    elif note_letter == 'e':
        n = note.Note('E4')
        n.duration = duration.Duration(0.5)
        s.append(n)
    elif note_letter == 'f':
        n = note.Note('F4')
        n.duration = duration.Duration(0.5)
        s.append(n)
    elif note_letter == 'g':
        n = note.Note('G4')
        n.duration = duration.Duration(0.5)
        s.append(n)

s = stream.Stream()
add_note('c')
add_note('d')
add_note('f')
add_note('g')
add_note('a')
add_note('d')
add_note('f')
add_note('g')
add_note('a')
add_note('d')
add_note('e')
add_note('g')
add_note('f')
add_note('b')
add_note('e')
add_note('g')
add_note('f')
add_note('a')
add_note('e')
add_note('g')
add_note('f')
add_note('a')
```

```
add_note('b')
add_note('d')
add_note('e')
add_note('b')
add_note('f')
add_note('a')
add_note('b')
add_note('d')
add_note('e')
add_note('b')
add_note('f')
add_note('f')

for j in range(0, 6):
    for i in s[(34*j):(34*(j+1))]:
        if i == c4:
            a = note.Note('B4')
            a.duration = duration.Duration(0.5)
            s.append(a)
        elif i == d4:
            a = note.Note('C4')
            a.duration = duration.Duration(0.5)
            s.append(a)
        elif i == e4:
            a = note.Note('D4')
            a.duration = duration.Duration(0.5)
            s.append(a)
        elif i == f4:
            a = note.Note('E4')
            a.duration = duration.Duration(0.5)
            s.append(a)
        elif i == g4:
            a = note.Note('F4')
            a.duration = duration.Duration(0.5)
            s.append(a)
        elif i == a4:
            a = note.Note('G4')
            a.duration = duration.Duration(0.5)
            s.append(a)
        elif i == b4:
            a = note.Note('A4')
            a.duration = duration.Duration(0.5)
            s.append(a)

s.show()
```

Code Block 1. Code to Produce the Fibonacci Music 1

```
from music21 import *

fibonacci = [1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, 1597, 2584,
4181, 6765, 10946, 17711, 28657, 46368, 75025, 121393, 196418, 317811, 514229,
832040, 1346269, 2178309, 3524578, 5702887, 9227465, 14930352, 24157817,
39088169, 63245986, 102334155, 165580141, 267914296, 433494437, 701408733,
1134903170, 1836311903, 2971215073, 4807526976, 7778742049, 12586269025,
20365011074, 32951280099, 53316291173, 86267571272, 139583862445,
225851433717, 365435296162, 591286729879, 956722026041, 1548008755920,
2504730781961, 4052739537881, 6557470319842, 10610209857723,
17167680177565, 27777890035288, 44945570212853, 72723460248141,
117669030460994, 190392490709135, 308061521170129, 498454011879264,
806515533049393, 1304969544928657, 2111485077978050, 3416454622906707,
5527939700884757, 8944394323791464, 14472334024676220,
23416728348467684, 37889062373143904, 61305790721611584,
99194853094755488, 160500643816367072, 259695496911122560,
420196140727489664, 679891637638612224, 1100087778366101888,
1779979416004713984, 2880067194370816000, 4660046610375530496,
7540113804746346496, 12200160415121876992, 19740274219868225536,
31940434634990100480, 51680708854858326016, 83621143489848426496,
135301852344706760704, 218922995834555203584, 354224848179261997056]
remainders = []

for i in fibonacci:
  remainders.append(i % 7)

s = stream.Stream()
def write_letter(n):
  if (n == 0):
     a = note.Note('C4')
     a.duration = duration.Duration(0.5)
     s.append(a)
  elif (n == 1):
     a = note.Note('D4')
     a.duration = duration.Duration(0.25)
     s.append(a)
  elif (n == 2):
     a = note.Note('E4')
     a.duration = duration.Duration(0.5)
     s.append(a)
  elif (n == 3):
     s.append(note.Note("F4"))
  elif (n == 4):
     s.append(note.Note("G4"))
  elif (n == 5):
     a = note.Note('A4')
     a.duration = duration.Duration(0.5)
     s.append(a)
  elif (n == 6):
```

```
    a = note.Note("B4")
    a.duration = duration.Duration(0.25)
    s.append(a)


for i in remainders:
  write_letter(i)

s.show()
```

Code Block 2. Code to Produce the Fibonacci Music 2

Authors' Contribution

The authors confirm that they equally contributed to this paper. In this study, the 1st and 2nd authors contributed to the conception, mathematical modeling, data collection, analysis, interpretation, and literature review. The 3rd and 4th authors contributed to the preparation of music files, EEG tests, and the writing of the manuscript.

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Conflict of Interest

The authors declare that there is no conflict of interest

Statement of Research and Publication Ethics

Research and publication ethics were observed in the study

Ethics Committee Approval Statement

The Ethical Committee Approval (Decision No: 25, Date: 31.03.2023) and the EEG Test process have been taken at the Erenköy Psychiatric Hospital.

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