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Binaural and/or Monophonic self-listening as a tool for music performance simulation: evaluating immersion and neural responses

Autoescuta binaural e/ou monofónica como ferramenta para simulação da performance musical: avaliação da imersão e respostas neurais

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Abstract: This exploratory study investigated the effects of binaural and monophonic self-listening on musicians' neural responses during the mental simulation of their own music performance. Six musicians participated in two EEG-monitored sessions in which they listened to binaural and monophonic recordings of their performances in a counterbalanced order. We hypothesized that binaural recordings, by preserving head-related transfer functions, would elicit stronger neural activation in spatial perception, emotional engagement, and motor simulation than monophonic recordings. The study examined differences in brain activity related to sensory, motor, and emotional processing between the two conditions. The results indicated that binaural self-listening induced broader cortical activation patterns aligned with sensorimotor and emotional processes. At the same time, monophonic recordings were associated with greater frontal activation linked to cognitive effort and attentional control. These findings suggest that binaural self-listening enhances mental performance simulation and may offer a promising tool for therapeutic interventions targeting music performance anxiety in contexts where physical practice is not feasible. Future research should employ larger samples and inferential analyses to strengthen these initial findings.

Keywords: binaural self-listening, binaural recording, music performance simulation; neural responses; electroencephalogram.

Resumo: Este estudo exploratório investigou os efeitos da autoescuta binaural e monofónica nas respostas cerebrais de músicos durante a simulação mental de suas próprias performances. Seis músicos participaram de sessões com EEG, escutando gravações binaurais e monofónicas de suas interpretações em ordem contrabalançada. Hipotetizou-se que as gravações binaurais, por preservarem as funções de transferência relacionadas à cabeça, induziriam uma ativação neural mais intensa relacionada à percepção espacial, envolvimento emocional e simulação motora. A atividade cerebral foi comparada entre os domínios sensorial, motor e emocional. A autoescuta binaural induziu uma ativação cortical mais ampla, associada a processos sensório-motores e emocionais, enquanto a autoescuta monofónica apresentou maior ativação frontal, ligada ao esforço cognitivo e controle atencional. Esses resultados sugerem que a autoescuta binaural potencializa a simulação mental da performance e pode apoiar estratégias terapêuticas para ansiedade na performance musical, especialmente quando a prática física não é viável. Investigações futuras devem recorrer a amostras de maior dimensão e a análises inferenciais, de modo a consolidar e testar de forma mais robusta estes resultados preliminares.

Palavras-chave: auto escuta binaural; gravação binaural; simulação da performance musical; respostas neurais; EEG (Eletroencefalograma).

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1 Introduction

Physiological and psychological skills, such as physical control and mental resilience, are essential for effective musical performance, ensuring both technical and emotional quality (Papageorgi; Kopiez, 2012). Meeting personal and collective expectations regarding these skills is a complex and arduous challenge, often triggering feelings of dissatisfaction that result in heightened and debilitating levels of music performance anxiety (MPA) (Ely, 1991; Papageorgi, 2021; Papageorgi; Creech; Welch, 2011; Papageorgi; Welch, 2020). High levels of MPA can trigger stress responses that impair public performance, regardless of the musician's experience (Fernholz et al., 2019; Kenny, Driscoll, Ackermann, 2014b). The prevalence of MPA is estimated to range from 16.5% to 60% among musicians and up to 83.1% among music students (Barros et al., 2022; Fernholz et al., 2019); both studies used self-reported assessments. MPA can be triggered by various factors, including the perception of high personal and collective expectations, which increases the complexity and challenge of delivering a high-quality musical performance (Barros et al., 2022; Castiglione; Rampullo; Cardullo, 2018; Ryan, 2021; Zhukov, 2019). Coping strategies are crucial, as a positive perception of performance can mitigate symptoms (Biasutti; Concina, 2014; Irie; Morijiri; Yoshie, 2023; Macafee; Comeau, 2023). Therefore, the development, exploration, and refinement of strategic approaches to managing MPA levels are vital during performance preparation to minimize its impact on musicians' lives and transform it, through control, into a beneficial factor for performance (Kenny, 2011; Kenny; Davis; Oates, 2004; Kenny; Arthey; Abbass, 2014a; Kokotsaki; Davidson, 2003).

Some training protocols for managing MPA are implemented without the performer playing their instrument, such as biofeedback training (Barros et al., 2018; Rabelo; Mármora; Ribeiro, 2018; Thurber et al., 2010; Wells et al., 2012), which requires maximum physiological relaxation to prevent movement from altering the monitored parameters (Borges et al., 2023). In this context, mental simulation emerges as a promising tool, since it can be combined with various approaches for the treatment of MPA (Hoffman; Hanrahan, 2012; Schaefer, 2015). Mental simulation has been widely recognized as a valuable strategy in music performance preparation, offering cognitive, emotional, and physiological benefits (Bernardi et al., 2012). It activates neural circuits related to motor planning, auditory imagery, and emotional processing, thereby enhancing technical skills, musical memory, and artistic expressiveness (Clark; Williamon, 2011; Toth et al., 2020). Research shows that mental practice can reduce physical strain, optimize study time, and improve performance confidence, especially when combined with physical practice or tools such as self-listening (Volioti; Williamon, 2016; Hewitt, 2001). Furthermore, mental simulation can serve as an effective coping strategy for music MPA, particularly when it includes mental rehearsal of the performance environment, promoting emotional resilience and reducing stress reactivity (Parreiras Gonçalves; Torchia Zanon, 2022). The use of recordings of one's own performance has also proven to be an effective tool for visualizing and mentally simulating a performance (Clark; Williamon, 2011).

The effectiveness of mental simulation, however, may vary according to individual visualization and concentration skills (Emmelkamp, 2013; Keller, 2012; Kosslyn et al., 1984). Techniques such as listening to recordings of oneself and practicing guided visualization can amplify the benefits, making them more effective (Clark; Williamon, 2011a; Guillot; Collet, 2005; Holmes; Collins, 2001). Self-listening has also proven to be a valuable tool in performance preparation, aiding musical awareness and refining technical and interpretive aspects (Hewitt, 2001; Volioti; Williamon, 2016). Borges et al. (2023) highlight the contribution of self-listening in mental performance simulation.

Based on the premise that binaural recordings capture sound in three dimensions, contributing to the perception of acoustic spatiality, immersive characteristics can be enhanced when the correct head-related transfer function (HRTF), specific to each individual, is considered during the recording process (Everest; Pohlmann, 2022; Rumsey, 2021). This study adopted an exploratory approach, aiming to gain an initial understanding of the neurophysiological effects of binaural listening in musicians. The hypothesis was that binaural recordings could elicit brain responses associated with more realistic and immersive auditory experiences compared to monophonic recordings. At this stage, the study sought to investigate whether these different auditory perspectives—binaural and monophonic—could serve as supportive tools for the mental simulation of musical performance in controlled environments, particularly in contexts where instrumental execution is not possible, such as in therapeutic protocols targeting MPA through neurofeedback and biofeedback techniques. Recent advances in music neuroscience have highlighted the complex neural mechanisms involved in musical listening, particularly through tools such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), which allow detailed observation of brain oscillations and connectivity during auditory experiences (Koelsch, 2011; Zatorre; Chen; Penhune, 2007). In this sense, the present study preliminarily explored the neurophysiological responses of musicians during self-listening to their musical performances in two distinct formats: monophonic and binaural, highlighting the particularities of each condition as an auxiliary tool in the mental simulation of musical performance, and contributing to intervention protocols for MPA in which active execution is not possible during treatment.

1.1 Mental Simulation

Understanding the different ways to simulate music performance is crucial for developing effective MPA management strategies. Performance simulation can take three primary forms: 1) Live Performance — recreating the actual performance situation (Kendrick et al., 1982; Wiederhold; Wiederhold, 2005), which can increase stress and anxiety, making MPA more difficult to control; 2) Virtual Performance Simulation — using technology such as augmented, virtual, and mixed reality, to offer a less intimate but more accessible alternative, with promising results in MPA control (Aufegger Et Al., 2017; Bissonnette et al., 2015, 2016; Fanger et al., 2020; Gorini; Riva, 2008; Orman, 2003, 2004; Owens; Beidel, 2015; Williamon; Aufegger; Eiholzer, 2014); 3) Mental Simulation — mental recreation of the performance that allows musicians to mentally rehearse and improve their skills without the pressure of a live audience, enhancing confidence and reducing MPA (Clark; Williamon, 2011b; Connoly; Williamon, 2004; Hoffman; Hanrahan, 2012; Immonen; Ruokonen; Ruismäki, 2012; Kosslyn et al., 1984; Osborne; Greene; Immel, 2014).

Several studies have focused on mental simulation and imagery (Clark; Williamon, 2011b; Connoly; Williamon, 2004; Hoffman; Hanrahan, 2012). Mental simulation focuses on the detailed practice of motor tasks and specific actions, enhancing muscle memory and psychological preparation, which is useful when physical practice is limited. By contrast, imagery involves creating vivid, sensory mental images that engage multiple senses, offering a rich, immersive mental experience (Keller, 2012; Mielke & Comeau, 2019). Mental simulation can help improve focus, manage MPA, and enhance real-life performance (Keller, 2012). Musical imagination activates brain areas involved in physical performance (Kristeva et al., 2003), mainly in auditory and motor regions (Tanaka; Kirino, 2022). However, the effectiveness of mental simulation can vary depending on individual strategies and skills in visualization and concentration (Emmelkamp, 2013; Keller, 2012; Kosslyn et al., 1984).

Self-listening is the process of listening to your own performance, whether live or via an audio recording (Hewitt, 2001). Borges et al. (2023) suggest that self-listening can serve as a “guiding thread,” providing an auditory foundation that facilitates more precise, contextually informed mental simulation. This approach is particularly beneficial in MPA management training programs that do not allow the use of the instrument during treatment sessions, such as biofeedback and neurofeedback training, which require physiological relaxation and participant immobility.

1.2 Binaural Recording and Listening

When considering self-listening as a tool for performance simulation, it is essential to account for spatiality, which can be captured in different ways, such as through stereo or binaural recordings. Using intensity and/or time cues, a two-channel stereo recording uses two channels (left and right) to create a sense of direction, allowing the listener to identify the source of sounds in space (Bartlett, 2016). Binaural recording simulates human hearing by using microphones positioned at the ears to capture sound in three dimensions (left–right, up–down, front–back), providing greater and more realistic immersion (Rumsey, 2021). According to Everest and Pohlmann (2022), the choice between stereo and binaural depends on the desired level of spatial realism, with binaural recording ideal for more immersive simulations, mainly when the performer’s individual HRTFs are used, thereby ensuring greater sound realism.

In recent years, binaural recording has been used in various studies investigating auditory perception and its neurological implications. Brinkmann et al. (2014) evaluated the perceptual authenticity of binaural simulations in reverberant environments, showing that this technology can be indistinguishable from real auditory experiences for certain types of sounds, such as the human voice. Additionally, research by Cheng and Wakefield (2001) explored the use of moving-sound-source synthesis with HRTFs, expanding the possibilities for spatial reproduction in musical applications and for auditory simulations in general.

The HRTF plays a fundamental role in describing how individual anatomy (head, ears, and torso) modifies sound as it reaches the ears, making it crucial for recreating spatial auditory experiences. The importance of this technology lies in its ability to provide a more immersive and realistic listening experience, making it valuable for areas such as virtual reality, headphone development, and neuroscientific research (Zieliński; Antoniuk; Lee, 2022). This method enables a three-dimensional perception of sound, accurately replicating the way we hear in the real world (Brinkmann et al., 2014). Preserving individual HRTFs in binaural recordings is crucial for creating realistic auditory simulations that are virtually indistinguishable from real experiences (Brinkmann et al., 2014). Studies show that the use of personalized HRTFs significantly improves sound localization perception, reducing spatial errors, especially in the median and front–back planes, compared with generic HRTFs (Grijalva et al., 2018; Kudo et al., 2006; Romigh et al., 2013). The lack of personalization can lead to poor spatial localization, as demonstrated by Yao and Chen (2013), who emphasize the importance of adjusting HRTFs to enhance auditory quality and precision. Moreover, Gan et al. (2017) stress that HRTF personalization is crucial for 3D audio rendering, improving spatial perception in augmented and virtual reality devices. Finally, Cheng and Wakefield (2001) demonstrated that using interpolated HRTFs enables the accurate reproduction of moving sound sources in electroacoustic environments, thereby enhancing spatial perception.

Binaural recordings have gained prominence in the field of musical performance because they create realistic acoustic simulations, allowing musicians to practice and interact with virtual environments. Examples include recreating historical acoustic spaces and simulating stage conditions to enhance musical perception and training (Chu, 2004; Martens; Woszczyk, 2004), as well as their use in online performances and remote recordings (Hagan, 2022; Mróz et al., 2022). Studies show that musicians respond differently to binaural auditory stimuli compared to non-musicians, suggesting significant potential for this technology in musical training (Ioannou et al., 2015). Furthermore, musicians have shown a preference for binaural audio over stereo due to the increased immersion it provides (Turchet; Tomasetti, 2023), and equalization has been identified as crucial for enhancing spatial perception, making the technology even more effective (Schärer; Lindau, 2009).

Binaural performance monitoring has also been studied and offers significant advantages over stereo: improved instrument localization, facilitating coordination in studios and remote collaborations (Turchet; Tomasetti, 2023); improved sound proximity and localization, benefiting rehearsals and live performances (Griesinger, 2016); a more realistic auditory scene compared to ambisonics (Thery, 2019); and increased immersion and enhanced musician performance during recording sessions (Bauer et al., 2022).

In general, binaural listening can enhance spatial perception and immersion during mental performance simulation. Zieliński et al. (2022) demonstrated that this technology improves the localization of sound sources in simulations, making it particularly useful for creating immersive experiences. A growing body of research highlights the versatility and impact of binaural self-listening both in simulations and live performance (monitoring). Furthermore, it can be used as an auxiliary tool in instrumental performance simulation during treatment protocols for performance anxiety when playing the instrument is impossible.

1.3 Neural Processing of Music self-listening

Research indicates that musical listening involves multiple neural processes that interact to shape the auditory experience. EEG and functional magnetic resonance imaging (fMRI) have enabled the identification of oscillatory patterns and connectivity between brain regions, thereby clarifying how the human brain processes music (Koelsch, 2011; Zatorre, Chen, Penhune, 2007). Almudena et al. (2021) analyzed the results of electroencephalographic investigations addressing music perception from various technical analytical perspectives. The main themes explored include intrinsic musical features, such as tonality, rhythm, dissonance, and musical syntax, as well as musical emotions, expectations, differences between pleasant and unpleasant music, and the effects of familiarity and musical experience. Thus, research primarily encompasses auditory perception, memory, cognition, emotion, motor processing, harmonic expectation, and sensory integration.

Auditory perception is primarily monitored by the primary and secondary auditory cortices, which analyze fundamental sound characteristics such as frequency, timbre, and intensity (Patterson et al., 2002; Zatorre; Belin, 2001). Furthermore, the secondary auditory cortex is essential for processing more complex patterns, including melody, rhythm, and harmony, facilitating the recognition and organization of musical stimuli (Hyde; Peretz; Zatorre, 2008; Koelsch, 2011).

Musical memory is also a central factor in auditory experience. It is strongly linked to the activity of the hippocampus and prefrontal cortex, regions associated with the storage and retrieval of musical information (Koelsch, 2011). Studies show that repeated exposure to a melody can lead to greater coherence in neural activity, reflecting memory encoding processes and pattern recognition (Zatorre; Chen; Penhune, 2007).

Regarding music cognition, music activates neural mechanisms shared with language, such as Broca's and Wernicke's areas, which process both linguistic syntax and musical syntax (Koelsch, 2011). This neural overlap suggests that the brain analyzes musical organization like that of spoken sentences.

Musical emotion is another widely studied aspect in music neuroscience. Research indicates that the amygdala and orbitofrontal cortex play fundamental roles in regulating emotions evoked by music (Koelsch, 2011). Additionally, variations in alpha (8–12 Hz) and beta (13–30 Hz) band activity have been associated with emotional differences in music perception, reflecting the involvement of these brain oscillations in the affective experience of music (Schaefer; Vlek; Desain, 2011; Lin et al., 2022).

Motor processing is also intrinsically linked to music listening, as motor regions are activated even when an individual is merely listening to music without moving. This activation of the motor cortex suggests that listening to musical rhythms triggers an internal simulation of movement, which may be related to our ability to anticipate and synchronize with rhythmic patterns (Zatorre; Chen; Penhune, 2007).

Harmonic expectation, in turn, involves the prefrontal cortex, which is responsible for predicting and detecting surprises in musical structure (Koelsch, 2011). The brain can anticipate harmonic changes based on previously learned patterns, activating neural networks involved in predicting musical events.

Finally, sensory integration enables listeners to combine auditory, motor, and emotional information to create a coherent and meaningful musical experience. The superior parietal cortex is involved in this process, enabling the fusion of different sensory stimuli and facilitating the understanding of musical structure within the context of the overall auditory experience (Zatorre; Chen; Penhune, 2007).

These studies demonstrate that music listening is not an isolated process but rather a complex interaction among distributed neural networks involving perception, cognition, memory, emotion, and motor processing. EEG has been a fundamental tool in mapping these interactions and understanding how music influences brain function at various levels. Most of the studies analyzed by Almudena et al. (2021) involved participants in a resting state, listening to musical excerpts, note sequences, or chords. A significant gap identified is the scarcity of studies investigating music perception in participants during music performance or imagined performance. Additionally, no studies were found that use self-listening of a performance combined with EEG monitoring to analyze musicians' perception.

Based on the immersive properties of binaural recordings and their ability to preserve individualized spatial cues, we hypothesized that binaural self-listening would promote stronger neural activation patterns associated with motor imagery, emotional engagement, and sensory integration, compared to traditional monophonic or usual stereo recordings.

2 Methods

2.1 Participants

The sample consisted of six musicians (three women and three men) from a Portuguese university, including three professors and three students, who played three different instruments. Each of the three instruments (cello, piano, and guitar) was represented by one professor and one student (Tab. 1). The professors held doctoral degrees, and the students were enrolled in bachelor's or master's programs. Given the small sample size (n=6), this study is intended as exploratory research. As such, the results should be interpreted with caution and viewed as preliminary evidence rather than definitive conclusions.

Tabela 1 – Participant sample characteristics

Participant	Role	Instrument	Gender	Age	Experience (years)	Performances per year	Degree
P1	Professor	Cello	Male	41	25	20	PhD
P2	Professor	Piano	Female	56	47	30	PhD
P3	Professor	Guitar	Male	45	30	30	PhD
P4	Student	Cello	Female	22	10	2	BA
P5	Student	Piano	Male	36	27	4	MA
P6	Student	Guitar	Female	25	15	4	BA

Source: Data from Author (2025).
Description of the image: table displaying sociodemographic and musical characteristics of participants, including role, instrument, gender, age, years of experience, annual performances, and academic degree.

Overall, the sample had a mean age of 37.5 years (SD = 12.7), 25.7 years of musical experience (SD = 12.9), and performed publicly an average of 15 times per year (SD = 13.3). They also self-reported good health and hearing. Participation was voluntary, and all participants were fully informed about the study procedures and provided written informed consent. The study was approved by the Ethics and Deontology Committee of the University of Aveiro (CED-UA), under approval no. 01-CED/2019. Participants also self-reported good health and hearing.

2.2 Procedures

Each participant was invited to prepare a piece of their choice from their own repertoire, with a maximum duration of 6 minutes, appropriate to their technical and interpretative level. The main selection criterion was that the musicians felt prepared, confident, and comfortable performing and recording the piece.

The study was conducted in two phases: 1) simultaneous audio recording of the participants' performances from binaural and stereo perspectives, and 2) EEG recordings while listening to the performance from the perspectives of binaural and monophonic.

2.2.1 Phase 1: audio recording of the performances

The musical performances were recorded simultaneously under two conditions: binaural and stereo. The recordings took place in a concert hall at the university, familiar to all participants and with favorable acoustic conditions, ensuring consistent reverberation time and sound diffusion for all recordings and participants. Before the recordings began, the microphones were calibrated, installed, and tested. Participants were then given 15 minutes to play their instruments freely, allowing them to adapt to the room and to the microphones attached to their ears.

After the adaptation period, the participants performed their pieces. Immediately after each performance, they rated their satisfaction on a scale from 1 (dissatisfied) to 10 (satisfied). Each participant had the opportunity to follow this recording protocol three times consecutively, allowing the researchers to select the best of the three performances for analysis in the study's second phase. The mean satisfaction rating for the most satisfying performance was 9 (SD = 1). No sound compensation was made between the different instruments in terms of volume levels, acoustic characteristics, or spatial positioning.

Recording performance: We used a Sound Devices MixPre 6 II recorder to capture both formats. Binaural recording was conducted using two Primo 173 omnidirectional microphones, each attached to the participants' auricle and cross-channel calibrated with a Bruel & Kjær Type 4231. For the stereo recording, we used two Rode NT2 microphones configured in an XY coincident pattern, placed in front of the instrument and aligned with its primary sound radiation angle, and subsequently summed to mono, following the principles of this type of recording. It is important to note that a specialist recommended this microphone configuration. The stereo microphones were positioned from an audience perspective, and channel summation to dual mono was adopted to limit spatial-intensity cues and support controlled EEG comparisons.

2.2.2 Phase 2: self-listening under binaural and monophonic conditions monitored by EEG

During the self-listening procedure, all participants completed two listening sessions of their performances, monitored by EEG, corresponding to the two different recording approaches implemented in the first phase. Two groups of three participants were formed to counterbalance years of experience. Each group included professors and students of each instrument, although in different proportions: one group comprised two professors and one student, and the other, two students and one professor. Participants listened to the same two recordings—one in binaural format and the other in mono—but in different orders. Specifically, one group listened to the binaural version first, followed by the monophonic version, while the other group began with the monophonic version and then listened to the binaural version.

Following EEG setup, preparation, and positioning, participants completed a baseline data collection, during which they were monitored for 6 minutes without any stimuli. During this period, they were asked to remain still for 3 minutes with their eyes open, and then for 3 minutes with their eyes closed. Before each listening session, participants were instructed to imagine their performance of the piece while simultaneously listening to the recording, remaining as still as possible to avoid interfering with EEG monitoring and data recording. During the listening sessions, participants were blindfolded to prevent visual input from generating EEG signal artifacts.

After baseline data collection, participants completed the first listening session for their assigned listening condition. At the end of this session, they completed an unrelated distractor task for approximately 30 minutes to minimize any carry-over effects. This task consisted of completing questionnaires on sociodemographic data, interests, and experiences related to wine tourism. Participants then viewed two slide shows (20 images of wine cellars and 20 of vineyards) while their brain activity was recorded via EEG. Finally, the second listening session was conducted, corresponding to the assigned listening condition for their participant group.

EEG recordings: the EEG recordings and data processing were carried out using specific hardware and software to ensure precision and efficiency at every stage. The hardware used was the ANT system with the 32-channel WaveGuard cap (ANT Neuro), offering high spatial resolution, superior signal quality, and adaptable comfort for participants. This technology provides comprehensive scalp coverage while simultaneously capturing electrical activity from multiple brain regions, which is essential for detailed analysis of brain responses. Data acquisition was performed using Asalab software, version 4.10.1, which allows signal recording, initial filtering, and artifact exclusion, using predefined cutoffs of -150 μV to 150 μV (Fabiani et al., 2009; Luck, 2014). Asalab provides real-time data control, ensuring the quality of signals captured and seamless integration with other software, such as standardized low-resolution brain electromagnetic tomography (sLORETA).

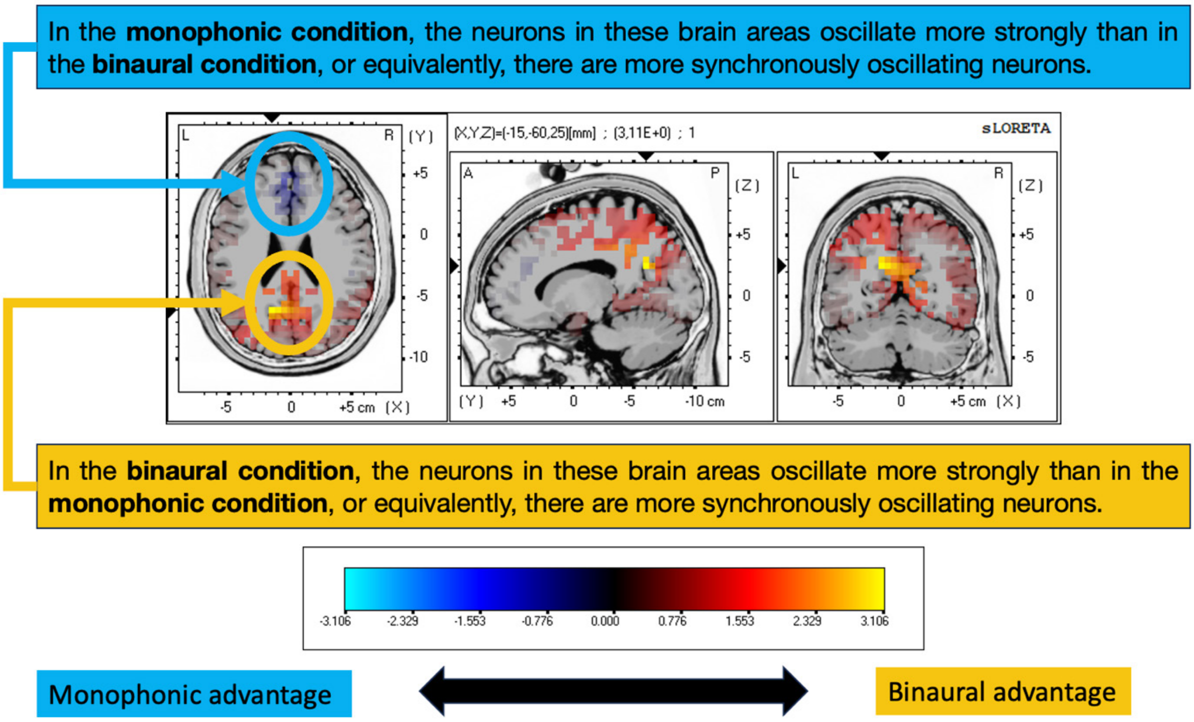
sLORETA: standardized low-resolution brain electromagnetic tomography (sLORETA) is a 3D source localization method developed to model and localize brain electrical activity from multichannel EEG recordings (Pizzagalli et al., 2001; Northoff et al., 2006; Northoff et al., 2006). sLORETA was developed by Pascual-Marqui and Lehmann (1994), Pascual-Marqui (1999, 2002), and Pascual-Marqui et al. (2002) to estimate the locations of neural generators underlying brain electrical activity using a maximally smooth linear inverse solution. This means that the algorithm assumes a more dispersed and continuous distribution of neural currents to minimize errors in reconstructing EEG signal sources. Validation studies of the sLORETA algorithm have shown that it can accurately estimate the location of neural sources, even in deep brain regions, as demonstrated by combined fMRI-EEG experiments (Vitacco et al., 2002). Mulert et al. (2004) used a classic oddball paradigm with pure tones to compare brain activations measured by fMRI with those estimated by sLORETA. Their results showed that sLORETA correctly localized the neural correlates of unimodal auditory stimuli, with minimal localization error. This error occurs due to the method's low spatial resolution, but its accuracy is sufficient for exploratory studies and functional EEG analyses.

sLORETA for EEG analysis and reporting: the exploratory analysis of brain activations during self-listening to binaural and monophonic auditory stimuli was conducted using sLORETA, allowing the identification of the cortical regions most involved in each listening condition. All reported activations were obtained by comparing participants' baselines, ensuring that the results reflect variations in neural activity induced by the auditory stimuli.

sLORETA software version v20210701 was used for source estimation, cortical distribution analysis, and calculation of activation averages across different brain regions. This software enabled the transformation of the cross-spectral data into files that allowed the evaluation of differences in oscillatory activity between binaural and monophonic listening conditions across all frequency bands: Delta (δ) (0.5–4 Hz); Theta (θ) (4–8 Hz); Alpha 1 (α1) (8–10 Hz); Alpha 2 (α2) (10–12 Hz); Beta 2 (β2) (18–25 Hz); Beta 3 (β3) (25–30 Hz). Activation averages were calculated directly in sLORETA. For each participant, cross-spectral values in each frequency band were summed across the regions of interest (ROI) and then divided by the total number of analyzed segments, yielding individual activation averages. These individual averages were then integrated to generate the group's overall average, reflecting the combined brain activation of all participants.

The results are presented through images and tables containing Talairach coordinates (X, Y, Z), voxel values, Brodmann areas (BA), cerebral lobes, and the structures most activated when listening to the stimuli. This information enables a comparative visualization of the different regions recruited under each sound condition. Brain regions highlighted in blue tones represent greater neural activation in the monophonic condition. In comparison, regions in red and yellow tones emphasize a greater neural activation in the binaural condition, as illustrated in Figure 1.

Figure 1 - sLORETA output.



In the **monophonic condition**, the neurons in these brain areas oscillate more strongly than in the **binaural condition**, or equivalently, there are more synchronously oscillating neurons.

In the **binaural condition**, the neurons in these brain areas oscillate more strongly than in the **monophonic condition**, or equivalently, there are more synchronously oscillating neurons.

Source: sLORETA/authors (2025)

Description of the image: Figure used as an example of sLORETA output showing the intracranial source differences between the monophonic and binaural conditions.

Data triangulation procedure: to improve understanding of neural dynamics across auditory conditions, a data triangulation process was conducted. This procedure organized cortical activations by frequency band and stimulus type (binaural and monophonic), identifying convergent and divergent regions. Brain structures were classified according to Brodmann areas, associated lobes, and the frequency bands in which they were activated.

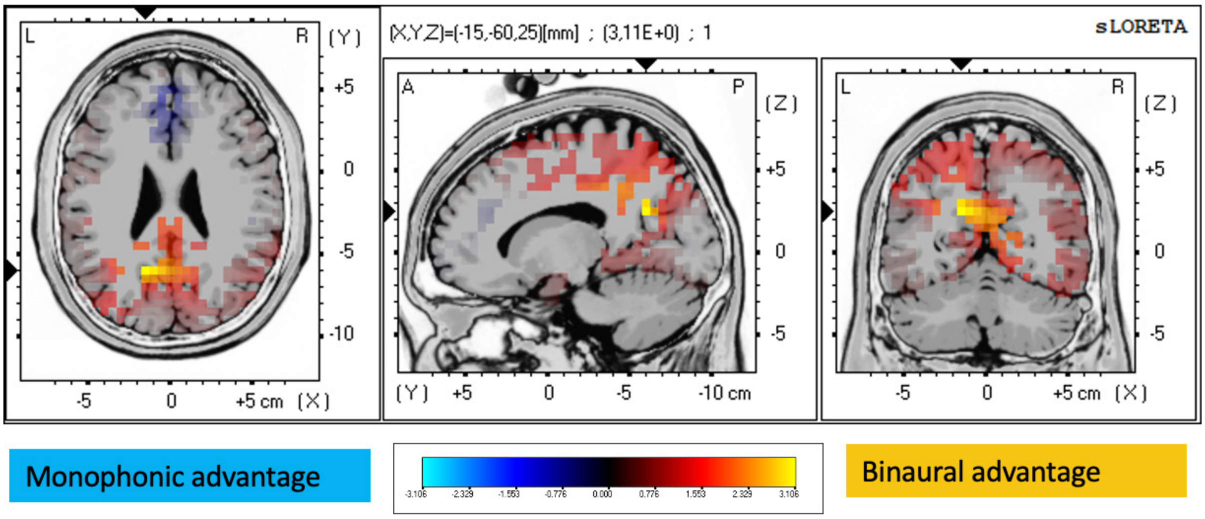
No inferential statistical analyses were conducted due to the exploratory nature of the study and the limited sample size. Visual inspection and descriptive analyses were used to identify trends and inform the direction of future research.

3 Results

The results indicate distinct activation patterns between the binaural and monophonic conditions, suggesting differences in auditory processing mechanisms and neural integration. Specifically, variations were observed in the regions of most significant activation across frequency bands, suggesting that each sound configuration may modulate cortical activity differently in musicians. Below, we present the activation maps generated by sLORETA, along with descriptive tables containing the five central regions activated for each frequency bands—Delta (δ) (0.5–4 Hz), Theta (θ) (4–8 Hz), Alpha 1 (α1) (8–10 Hz), Alpha 2 (α2) (10–12 Hz), Beta 2 (β2) (18–25 Hz), and Beta 3 (β3) (25–30 Hz)—and self-listening condition (binaural and monophonic).

3.1 Delta band (δ) (0.5–4 Hz).

Figure 2 – Delta band (δ) (0.5–4 Hz) brain scan.



Source: sLORETA/authors (2025).
Description of the image: comparison of delta band (δ) (0,5 - 4 Hz) activations between monophonic and binaural self-listening.

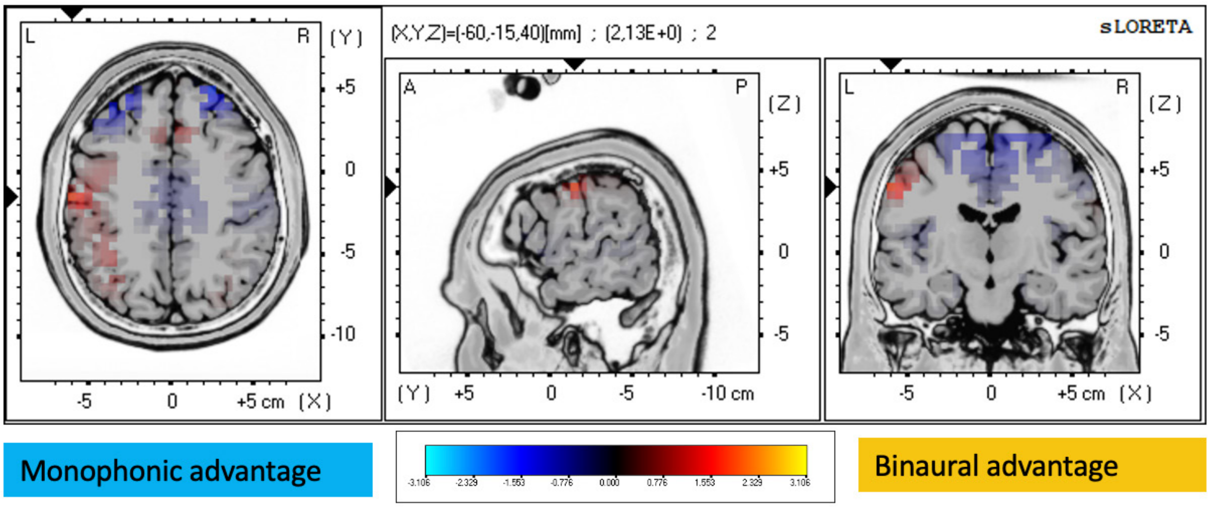
Tabela 2 – Delta band (δ) (0.5–4 Hz) results.

	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
Delta band Monophonic	45	-8	37	-1.32080	6	Frontal Lobe	Precentral Gyrus
	0	45	25	-1.28187	9	Frontal Lobe	Medial Frontal Gyrus
	-5	45	21	-1.24312	9	Frontal Lobe	Medial Frontal Gyrus
	45	-8	33	-1.22889	6	Frontal Lobe	Precentral Gyrus
	45	-12	42	-1.20153	4	Frontal Lobe	Precentral Gyrus
Delta band Binaural	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
	-15	-57	26	3.10566	31	Limbic Lobe	Precuneus
	-10	-57	26	2.99041	31	Occipital Lobe	Precuneus
	-15	-57	30	2.92863	31	Limbic Lobe	Precuneus
	-50	-33	20	2.91854	13	Sub-lobar	Insula
	-35	-42	34	2.85009	40	Parietal Lobe	Sub-Gyral

Source: sLORETA/authors (2025).
Description of the image: five brain areas showing the strongest synchronous neuronal activity in the delta band during monophonic and binaural self-listening.

3.2 Theta band (θ) (4–8 Hz)

Figure 3 – Theta band (θ) (4–8 Hz) brain scan.



Source: sLORETA/authors (2025).
Description of the image: comparison of theta band (θ) (4–8 Hz) activations between monophonic and binaural self-listening.

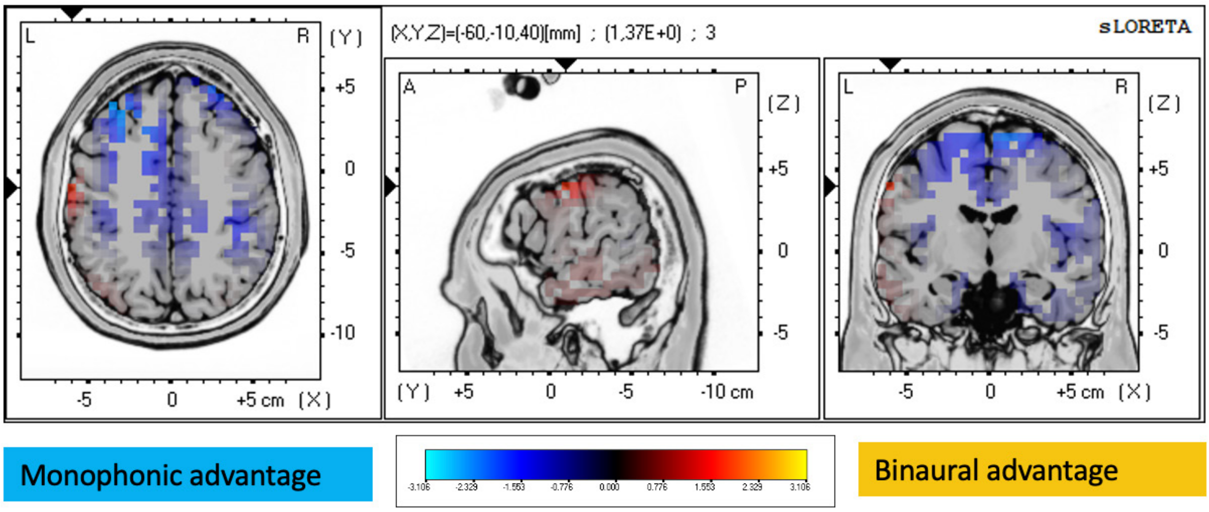
Tabela 3 – Theta band (θ) (4–8 Hz) results.

	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
Theta band Monophonic	-50	15	8	-3.62649	44	Frontal Lobe	Precentral Gyrus
	-50	20	4	-3.50839	45	Frontal Lobe	Inferior Frontal Gyrus
	-54	19	-1	-3.47897	47	Frontal Lobe	Inferior Frontal Gyrus
	-50	15	-1	-3.46982	47	Frontal Lobe	Inferior Frontal Gyrus
	-45	15	8	-3.04628	44	Frontal Lobe	Precentral Gyrus
Theta band Binaural	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
	-59	-13	37	2.13435	4	Frontal Lobe	Precentral Gyrus
	-54	-13	37	1.93863	4	Frontal Lobe	Precentral Gyrus
	-54	-18	38	1.80261	3	Parietal Lobe	Postcentral Gyrus
	-54	-13	33	1.75852	4	Frontal Lobe	Precentral Gyrus
	-50	-13	37	1.58895	4	Frontal Lobe	Precentral Gyrus

Source: sLORETA/authors (2025).
Description of the image: five brain areas showing the strongest synchronous neuronal activity in the theta band during monophonic and binaural self-listening.

3.3 Alpha 1 band (α1) (8–10 Hz)

Figure 4 – Alpha 1 band (α1) (8–10 Hz) brain scan.



Source: sLORETA/authors (2025).
Description of the image: comparison of alpha 1 band (α1) (8 - 10 Hz) activations between binaural and monophonic self-listening.

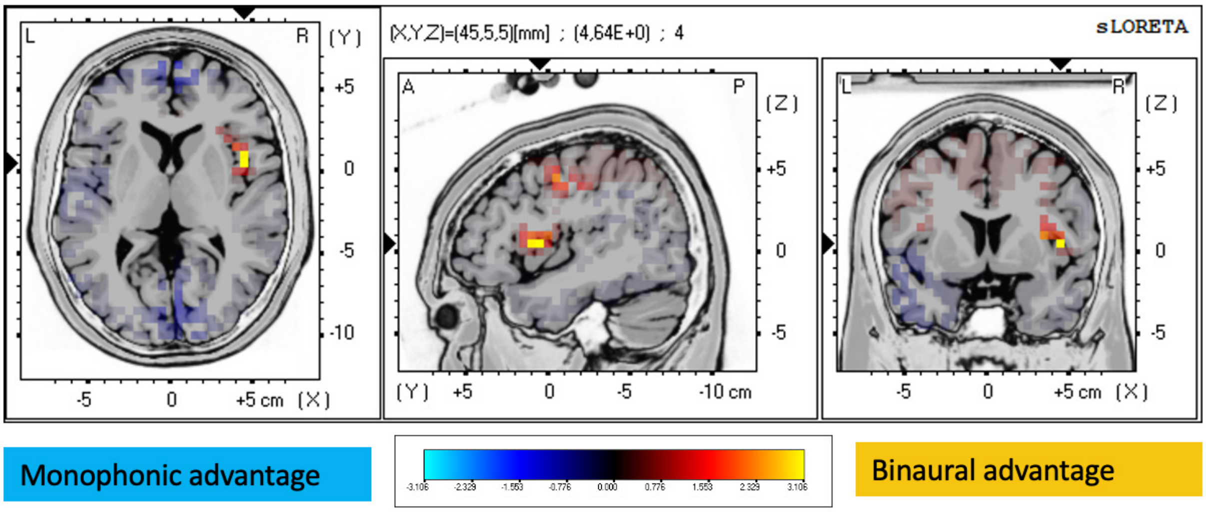
Tabela 4 – Alpha 1 band (α1) (8–10 Hz) results.

	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
Alpha band 1 Monophonic	-30	36	40	-2.36748E	8	Frontal Lobe	Middle Frontal Gyrus
	-35	45	30	-2.32785E	9	Frontal Lobe	Superior Frontal Gyrus
	-25	36	40	-2.20038E	8	Frontal Lobe	Middle Frontal Gyrus
	-25	31	40	-2.13616E	8	Frontal Lobe	Middle Frontal Gyrus
	-40	45	25	-2.13109E	10	Frontal Lobe	Middle Frontal Gyrus
Alpha band 1 Binaural	X(TAL),	Y(TAL),	Z(TAL),	Voxel Value	BA	Lobe	Structure
	-59	-8	37	1.36793E	6	Frontal Lobe	Precentral Gyrus
	-59	-13	37	1.25898E	4	Frontal Lobe	Precentral Gyrus
	-59	-13	33	1.15576E	4	Frontal Lobe	Precentral Gyrus
	-54	-13	33	1.06633E	4	Frontal Lobe	Precentral Gyrus
	-59	-18	38	1.04848E	4	Frontal Lobe	Precentral Gyrus

Source: sLORETA/authors (2025).
Description of the image: five brain areas showing the strongest synchronous neuronal activity in the alpha 1 band (α1) (8–10 Hz) during monophonic and binaural self-listening.

3.4 Alpha 2 band (α2) (10–12 Hz)

Figure 5 – Alpha 2 band (α2) (10–12 Hz) brain scan.



Source: sLORETA/authors (2025).
Description of the image: comparison of alpha 2 band (β2) (10 - 12 Hz) activations between binaural and monophonic self-listening.

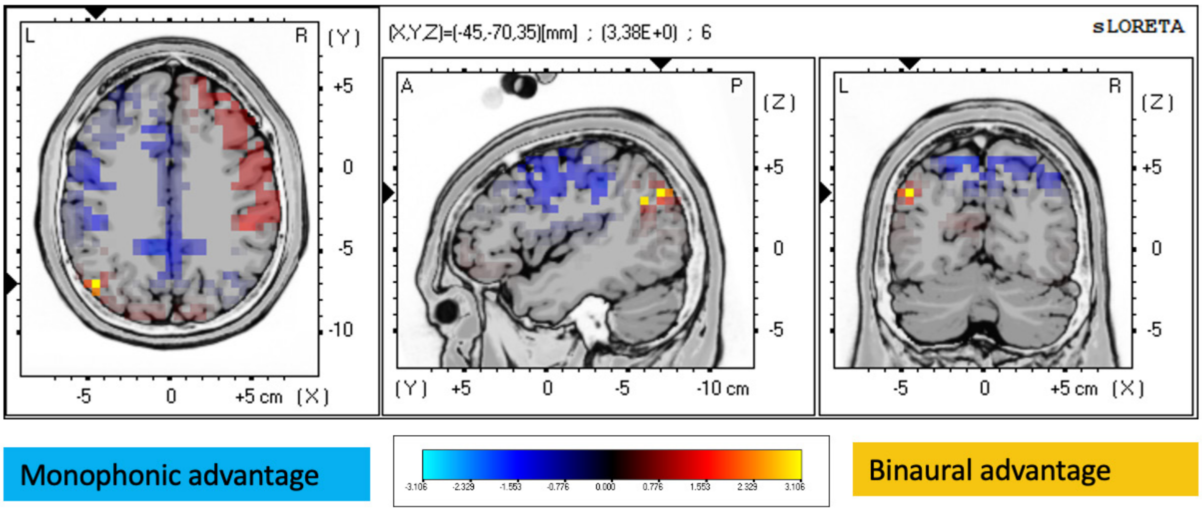
Tabela 5 – Alpha 2 band (α2) (10–12 Hz) results.

	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
Alpha band 2 Monophonic	5	64	11	-2.37594	10	Frontal Lobe	Medial Frontal Gyrus
	5	59	11	-2.35781	10	Frontal Lobe	Medial Frontal Gyrus
	10	64	11	-2.32757	10	Frontal Lobe	Medial Frontal Gyrus
	5	64	15	-2.32204	10	Frontal Lobe	Medial Frontal Gyrus
	5	59	6	-2.29986	10	Frontal Lobe	Medial Frontal Gyrus
	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
Alpha band 2 Binaural	45	5	4	4.64078	13	Sub-lobar	Insula
	45	10	4	4.54368	13	Sub-lobar	Insula
	40	0	9	3.91919	13	Sub-lobar	Insula
	35	5	9	3.52575	13	Sub-lobar	Insula
	45	-3	42	3.48467	6	Frontal Lobe	Precentral Gyrus

Source: sLORETA/authors (2025).
Description of the image: five brain areas showing the strongest synchronous neuronal activity in the alpha 2 band during monophonic and binaural self-listening.

3.5 Beta 2 band (β2) (18–25 Hz)

Figure 6 – Beta 2 band (β2) (18–25 Hz) brain scan.



Source: sLORETA/authors (2025).
Description of the image: comparison of beta 2 band (β2) (18–25 Hz) activations between binaural and monophonic self-listening.

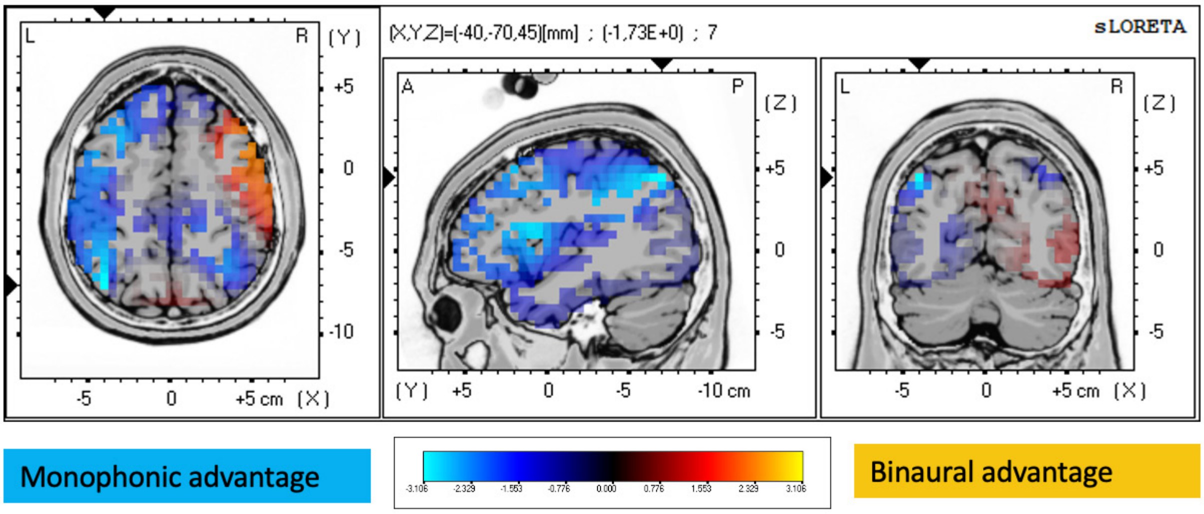
Tabela 6 – Beta 2 band (β2) (18–25 Hz) results.

Beta band 2 Monophonic	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
	-10	-56	49	-2.23235	7	Parietal Lobe	Precuneus
	-50	-36	48	-2.22845	40	Parietal Lobe	Inferior Parietal Lobule
	-50	-37	43	-2.22530	40	Parietal Lobe	Inferior Parietal Lobule
	-10	-56	53	-2.17543	7	Parietal Lobe	Precuneus
	-15	-56	49	-2.17462	7	Parietal Lobe	Precuneus
Beta band 2 Binaural	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
	-45	-66	36	3.38287	39	Parietal Lobe	Angular Gyrus
	-45	-57	30	3.23414	39	Temporal Lobe	Superior Temporal Gyrus
	-50	-61	40	2.59142	39	Parietal Lobe	Inferior Parietal Lobule
	-45	-71	36	2.57049	39	Parietal Lobe	Angular Gyrus
	-40	-57	26	2.51595	39	Temporal Lobe	Superior Temporal Gyrus

Source: sLORETA/authors (2025).
Description of the image: five brain areas showing the strongest synchronous neuronal activity in the beta 2 band during monophonic and binaural self-listening.

3.6 Beta 3 band (β3) (25–30 Hz)

Figure 7 – Beta 3 band (β3) (25–30 Hz) brain scan.



Source: sLORETA/authors (2025).
Description of the image: comparison of beta 3 band (β3) (25–30 Hz) activations between binaural and monophonic self-listening.

Tabela 7 – Beta 3 band (β3) (25–30 Hz) results.

	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
Beta band 3 Monophonic	-40	-66	45	-1.72677	7	Parietal Lobe	Inferior Parietal
	-40	-61	45	-1.70036	40	Parietal Lobe	Inferior Parietal
	-35	6	14	-1.69341	13	Sub-Lobar	Insula
	-35	6	18	-1.65012	13	Sub-Lobar	Insula
	-35	10	13	-1.64821	13	Sub-Lobar	Insula
Beta band 3 Binaural	X(TAL)	Y(TAL)	Z(TAL)	Voxel Value	BA	Lobe	Structure
	35	15	-1	1.59617	13	Sub-Lobar	Insula
	55	19	-1	1.58762	47	Sub-Lobar	Extra-Nuclear
	40	15	-1	1.57985	13	Sub-Lobar	Insula
	45	19	-1	1.57704	47	Frontal Lobe	Inferior Frontal Gyrus
	40	-14	-5	1.57387	47	Sub-Lobar	Insula

Source: sLORETA/authors (2025).
Description of the image: five brain areas showing the strongest synchronous neuronal activity in the beta 3 band during monophonic and binaural self-listening.

3.7 Convergent and divergent activations between self-listening stimuli

Triangulation of the data revealed patterns of convergent and divergent cortical activations between binaural and monophonic self-listening conditions. Table 8 systematically organizes this information, facilitating interpretation and enabling the decoding of the functional specificities associated with each type of self-listening.

Tabela 7 – Cortical structures activated across frequency bands during binaural and monophonic self-listening.

Structure	Brodmann Area (BA)	Frequency Band	Lobe	Stimulus Type
Precentral Gyrus	BA 4, 6	Delta	Frontal	Both
Insula	BA 13	Beta 3	Sub-lobar	Both
Precuneus	BA 31	Delta	Parietal/Limbic	Binaural
Sub-Gyral	BA 40	Delta	Parietal/Limbic	Binaural
Precentral Gyrus	BA 4	Theta	Frontal	Binaural
Postcentral Gyrus	BA 3	Theta	Parietal	Binaural
Precentral Gyrus	BA 4, 6	Alpha 1	Frontal	Binaural
Insula	BA 13	Alpha 2	Sub-lobar	Binaural
Precentral Gyrus	BA 6	Alpha 2	Frontal	Binaural
Superior Temporal Gyrus	BA 39	Beta 2	Temporal	Binaural
Angular Gyrus	BA 39	Beta 2	Parietal	Binaural
Inferior Parietal Lobule	BA 39	Beta 2	Parietal	Binaural
Extra-Nuclear	BA 47	Beta 3	Sub-lobar	Binaural
Medial Frontal Gyrus	BA 9	Delta	Frontal	Monophonic
Precentral Gyrus	BA 44	Theta	Frontal	Monophonic
Inferior Frontal Gyrus	BA 45, 47	Theta	Frontal	Monophonic
Medial Frontal Gyrus	BA 10, 8	Alpha 1	Frontal	Monophonic
Superior Frontal Gyrus	BA 9	Alpha 1	Frontal	Monophonic
Medial Frontal Gyrus	BA 10	Alpha 2	Frontal	Monophonic
Precuneus	BA 7	Beta 2	Parietal/Limbic	Monophonic
Inferior Parietal Lobule	BA 40	Beta 2	Parietal	Monophonic
Inferior Parietal	BA 40, 7	Beta 3	Parietal	Monophonic
Inferior Frontal Gyrus	BA 47	Beta 3	Frontal	Monophonic

Source: sLORETA/authors (2025).
Description of the image: Cortical structures activated across frequency bands (Delta, Theta, Alpha 1, Alpha 2, Beta 2, Beta 3) during binaural and monophonic self-listening. The type of stimulus indicates whether activation was exclusive to one condition or common to both.

Common activations were identified in the precentral gyrus (BA 4, 6) in the delta band, and in the insula (BA 13) in the beta 3 band. Binaural self-listening showed predominant activations in more widespread regions such as the precuneus (BA 31), insula (BA 13), angular gyrus (BA 39), and superior temporal gyrus (BA 39). In contrast, monophonic self-listening revealed greater recruitment of frontal regions, including the medial frontal gyrus (BA 9, 10), superior frontal gyrus (BA 9), and inferior frontal gyrus (BA 45, 47). These findings are further detailed and discussed in the following section.

4 Discussion

This exploratory study investigated whether binaural self-listening of a performance, by preserving more realistic spatial characteristics, could elicit neurophysiological responses more closely aligned with actual music performance situations, thereby contributing more effectively to the mental simulation process of music performance than monophonic self-listening. The results provide preliminary evidence supporting this hypothesis, indicating that binaural listening is associated with a more distributed cortical activation pattern that is functionally aligned with motor simulation, sensory integration, and emotional engagement. In contrast, monophonic listening revealed greater involvement of frontal regions associated with cognitive effort and executive control.

Analysis of cortical activations by structure revealed distinct patterns between binaural and monophonic listening stimuli. The precentral gyrus (BA 4 and 6) emerged as one of the regions most responsive to auditory stimuli, with activations distributed across various frequency bands. In the binaural condition, BA 6 was activated in the alpha 1 and alpha 2 bands, suggesting its involvement in motor imagery processes, action planning, and attentional coordination. Studies indicate that reduced alpha power in motor regions during motor imagery tasks — a phenomenon known as event-related desynchronization (ERD) — is widely recognized as an indicator of functional cortical activation (Stecklow; Infantosi; Cagy, 2007; Deiber et al., 2012). Guided auditory tasks have also shown that increased alpha activity may be associated with efficient sensorimotor engagement, especially in immersive contexts such as binaural listening (Zhou et al., 2022). BA 4 was activated in the theta and alpha 1 bands, a pattern consistent with its role in motor readiness and simulation of voluntary movement. Although classically associated with physical execution, fMRI studies show that BA 4 can also be recruited during imagined motor planning, involving subregions 4a and 4p (Sharma et al., 2008).

Furthermore, EEG recordings show alpha-band desynchronization in the sensorimotor region during motor imagery tasks, indicating functional activation even in the absence of actual movement (Formaggio et al., 2010; Yuan et al., 2010). Conversely, in monophonic conditions, activation of the same gyrus was observed in the delta band, particularly in BA 6, whose role in motor simulation under high cognitive load and in inhibitory control mechanisms is supported by EEG and fMRI research (Piano et al., 2017; Tanaka et al.; Honda et al.; Sadato et al., 2005). BA 44 was recruited explicitly in the theta band, consistent with its involvement in speech motor planning, executive functions, and directed auditory attention (Pardo et al., 1990). The combined presence of delta and theta activity in this region may reflect a greater cognitive effort during the simulation of musical performance under monophonic conditions (Harmony, 2013). In monophonic or spatially co-located conditions, the reduced availability of spatial/binaural cues is associated with increased listening effort and attentional demands during auditory scene analysis, compared with conditions that preserve binaural spatial cues (Rennies; Kidd Junior, 2018; Krueger et al., 2022; Koelewijn et al., 2015; Feuerstein, 1992; Bremen; Middlebrooks, 2013; Litovsky, 2012; Fintor, 2022).

These findings suggest that while binaural listening enhances neural mechanisms related to efficient motor simulation and sensorimotor engagement, monophonic listening requires greater executive resource recruitment and cognitive control during simulation. This implies that binaural self-listening facilitates automatic motor simulation, whereas monophonic listening requires more cognitive effort.

The precuneus was engaged in both conditions, albeit across different frequency bands. During binaural listening, BA 31 was activated in the delta band, associated with consciousness, mental imagery, autobiographical memory, and the functioning of the default mode network (DMN) (Cavanna, 2007). This region also plays a crucial role in integrating internal and external processes, as shown by its functional connectivity with sensory, emotional, and executive networks in highly trained musicians, especially during introspective and self-referential states (Tanaka; Kirino, 2016). Delta band activity in the precuneus is recognized as an electrophysiological marker of conscious states and automatic environmental monitoring (Danielson; Guo; Blumenfeld, 2011; Bonfiglio et al., 2013), reinforcing the idea that binaural listening promotes deep sensory immersion. In the monophonic condition, activation of BA 7 in the beta 2 band was observed, consistent with its role in integrating spatial information and visuomotor coordination, particularly in tasks involving bimanual action planning and spatial cognition (Le et al., 2017). Beta band activity (including beta 2) is also linked to visuomotor attention and motor preparation, especially in imagery and visual-motor control tasks (Baravalle; Rosso; Montani, 2018). Hence, BA 7 activation during monophonic listening may indicate compensatory efforts in spatial attention and motor control to support performance simulation in the absence of natural spatial cues.

The insula (BA 13) was activated in both conditions in the beta 3 band, consistent with its role in transforming auditory signals into emotional experiences, particularly in its anterior portion (Zhang et al., 2019). However, only binaural listening elicited additional activation in the alpha 2 band—a frequency associated with internal engagement during emotional tasks, possibly reflecting heightened sensory immersion (Schreiter; Chmielewski; Beste, 2018). This activation pattern indicates that binaural self-listening supports a more vivid and self-referential simulation of the musical experience.

The inferior frontal gyrus (BA 45, 47), predominantly recruited during monophonic listening, plays a key role in executive functions such as inhibitory control, focused attention, and response regulation under high cognitive load (Penfold et al., 2015). Activity in the theta and beta 3 bands within these areas underscores their involvement in inhibitory modulation (Dippel et al., 2017a, 2017b) and in managing perceptual and response conflicts (Daniel et al., 2023). In the context of monophonic listening — characterized by the absence of natural spatial cues — such conflict may stem from discrepancies between the musician's auditory expectations and the perceived stimulus, requiring greater engagement of the inferior frontal gyrus to preserve the coherence of mental simulation. This executive coordination appears to be mediated by communication between prefrontal regions and the subthalamic nucleus via theta and beta oscillations (Zavala et al., 2018), suggesting that monophonic listening imposes a heavier cognitive burden on sustaining music performance simulation.

The inferior parietal lobule displayed distinct activation profiles across listening conditions, reflecting divergent processing of auditory stimuli in spatial and sensory dimensions. In the binaural condition, activation of BA 39 was noted, encompassing the angular gyrus and the inferior parietal lobule, areas linked to multisensory integration and symbolic spatial representation (Caspers et al., 2008), as well as spatial cognition and manipulation of abstract mental constructs (Seghier, 2013). Such activation may reflect enhanced engagement of the attentional network and the construction of a more accurate spatial representation during self-listening. By contrast, monophonic listening elicited activity in BA 40 and BA 7, associated with reflexive attention and automatic detection of relevant stimuli in peripersonal space (Chambers et al., 2007). These areas are involved in auditory localization and three-dimensional sound processing, including orientation and spatial sound perception (Sato et al., 2011; Lewald et al., 2011).

However, these activations were less consistent — or even negative — than in the binaural condition, possibly indicating a less integrated and spatially impoverished sensory experience (Koizumi; Amano; Komatsu, 2019; Fox et al., 2005).

Studies such as Heine et al. (2021) and Callan et al. (2013) have demonstrated that spatialized sounds generated through HRTFs — by convolution or individual modeling — provoke activation in auditory and parietal areas associated with spatial perception and auditory attention (e.g., posterior superior temporal gyrus, BA 7, insula, and precuneus). The present study builds on this by examining binaural music self-listening, recorded from the performer's auditory perspective. Unlike earlier studies that relied on artificial stimuli and simple auditory tasks, the current protocol employed realistic, complex, and personally meaningful musical content, simulating a performance setting with high ecological validity—an element often absent from conventional auditory perception research (Koelsch, 2011; Almudena et al., 2021).

Although individualized HRTFs were not employed, the study used in situ binaural recordings with microphones attached to participants' ears, thereby preserving the natural spatial and reverberation characteristics of the listening experience. This ecologically grounded method aligns with findings that highlight the engagement of distributed neural systems — including auditory, motor, emotional, and cognitive networks — during music perception (Koelsch, 2011; Zatorre; Chen; Penhune, 2007).

Specifically, the activation of regions such as the precentral and inferior frontal gyri may reflect the motor simulation of performance, supported by evidence showing that passive music listening can recruit motor regions, suggesting internal rehearsal or predictive coding of rhythmic patterns (Zatorre; Chen; Penhune, 2007). The insula and the inferior parietal lobule are also part of a network responsible for sensory integration and spatial attention, previously implicated in music listening, which involves emotional and multimodal processing (Schaefer; Vlek; Desain, 2011; Zatorre; Chen; Penhune, 2007). Moreover, the involvement of the precuneus and parietal cortices may reflect the integration of sensory, motor, and spatial features into a coherent musical experience, consistent with models of music cognition and memory that emphasize the roles of these structures (Koelsch, 2011; Hyde; Peretz; Zatorre, 2008; Almudena et al., 2021).

Our results, therefore, not only support previous findings on spatial auditory processing using HRTF-based stimuli, but also contribute new evidence that ecologically valid, self-referential musical stimuli, such as binaural recordings of one's own performance, may more fully engage the multisensory and sensorimotor networks involved in music perception, memory encoding, and emotional processing. These findings suggest that binaural self-listening may be integrated into mental practice protocols for musicians, particularly in situations where instrument use is restricted, such as biofeedback and neurofeedback training for music MPA. By enhancing the realism and emotional resonance of auditory imagery, binaural recordings could help musicians engage more deeply in mental simulation, potentially improving performance quality and reducing anxiety levels.

Despite the study's interesting and promising findings, it presents several methodological limitations that should be considered when interpreting the results. The most significant of these concerns the lack of inferential statistical testing of cortical activation data. The analysis was based on visual inspection of distribution images generated by sLORETA and the identification of the top five activation foci per frequency band, without applying quantitative comparisons between conditions. Additionally, while sLORETA is useful for initial estimations of cortical localization, it has limited spatial resolution, particularly for subcortical structures or adjacent cortical regions (Pascual-Marqui, 2002; Vitacco et al., 2002; Mulert et al., 2004). Finally, although the use of personalized binaural recordings represents an advance in ecological realism, it also imposes a practical limitation: the applicability of the results depends on the feasibility of using recordings captured with each participant's individual HRTF. These limitations underscore the exploratory nature of the study and highlight essential directions for methodological refinement in future research.

The findings suggest that binaural self-listening of music performances promotes a cortical activation pattern more closely aligned with mental performance simulation processes, such as motor imagery, sensory integration, and emotional engagement. In turn, monophonic listening was associated with greater activation in executive control regions, indicating a potentially more cognitively demanding auditory experience. These results highlight the potential of binaural self-listening as a complementary tool for mental practice, particularly for addressing MPA in contexts where instrument use is restricted, such as in biofeedback and neurofeedback training. However, the exploratory nature of the study, marked by the absence of inferential statistical analyses and the limited spatial resolution of sLORETA, underscores the need for methodological refinement. Future research should expand the sample size, apply appropriate statistical tests (e.g., paired t-tests or permutation tests with FDR correction), and incorporate subjective measures such as perceived realism, presence, and attentional effort to better relate cortical responses to conscious experience. Building on the present findings, future studies with larger samples should explicitly compare monophonic, stereo, and binaural listening conditions, with a targeted focus on the specific brain regions identified here, enabling a more precise and hypothesis-driven mapping of their neurophysiological correlates. Additionally, comparisons between different spatialization methods, such as real binaural recordings, synthesized HRTFs, and binaural beats, and the integration of other neuroimaging techniques like fMRI could enhance both the accuracy and applicability of findings.

Overall, this study broadens the scope of personalized spatial sound in musical performance research and opens promising avenues for its use in therapeutic and educational settings.

References

ALMUDENA, G.; MANUEL, S.; GONZÁLEZ, J. J. EEG analysis during music perception. In: NAKANO, H. (Ed.). **Electroencephalography – From Basic Research to Clinical Applications**. IntechOpen, 2021. DOI: https://doi.org/10.5772/intechopen.94574.

AUFEGGER, L.; PERKINS, R.; WASLEY, D.; WILLIAMON, A. Musicians' perceptions and experiences of using simulation training to develop performance skills. **Psychology of Music**, v. 45, n. 3, p. 417-431, 2017. DOI: https://doi.org/10.1177/0305735616666940.

BARAVALLE, R.; ROSSO, O. A.; MONTANI, F. Rhythmic activities of the brain: Quantifying the high complexity of beta and gamma oscillations during visuomotor tasks. **Chaos**, v. 28, n. 7, p. 075513, 2018. DOI: https://doi.org/10.1063/1.5025187.

BARROS, S.; MARINHO, H.; BORGES, N.; PEREIRA, A. Characteristics of music performance anxiety among undergraduate music students: A systematic review. **Psychology of Music**, v. 50, n. 6, p. 2021-2043, 2022. DOI: https://doi.org/10.1177/03057356211066967.

BARROS, S.; MARINHO, H.; PEREIRA, A.; RIBEIRO, A.; SOUTO, I. A ansiedade na performance musical de música de câmara: O efeito do biofeedback como medida interventiva. **Revista Contexto & Saúde**, v. 19, n. 36, p. 120-126, 2018. DOI: https://doi.org/10.21527/2176-7114.2019.36.120-126.

BARTLETT, B.; BARTLETT, J. **Practical recording techniques: The step-by-step approach to professional audio recording**. 7. ed. Routledge, 2016. DOI: https://doi.org/10.4324/9781315696331.

BAUER, V.; SOUDOPLATOFF, D.; MENON, L.; PRAS, A. Binaural headphone monitoring to enhance musicians' immersion in performance. In: KATZ, B. F. G.; MAJDAK, P. (Eds.). **Advances in fundamental and applied research on spatial audio**. IntechOpen, 2022. DOI: https://doi.org/10.5772/intechopen.104845.

BERNARDI, N.; SCHORIES, A.; JABUSCH, H.-C.; COLOMBO, B.; ALTENMÜLLER, E. Mental practice in music memorization: An ecological-empirical study. **Music Perception**, v. 30, n. 3, p. 275-290, 2012. DOI: https://doi.org/10.1525/mp.2012.30.3.275.

BIASUTTI, M.; CONCINA, E. The role of coping strategy and experience in predicting music performance anxiety. **Musicae Scientiae**, v. 18, n. 2, p. 189-202, 2014. DOI: https://doi.org/10.1177/1029864914523282.

BISSONNETTE, J.; DUBÉ, F.; PROVENCHER, M. D.; MORENO SALA, M. T. Virtual reality exposure training for musicians: Its effect on performance anxiety and quality. **Medical Problems of Performing Artists**, v. 30, n. 3, p. 169-177, 2015. DOI: https://doi.org/10.21091/mppa.2015.3032.

BISSONNETTE, J.; DUBÉ, F.; PROVENCHER, M. D.; MORENO SALA, M. T. Evolution of music performance anxiety and quality of performance during virtual reality exposure training. **Virtual Reality**, v. 20, n. 1, p. 71-81, 2016. DOI: https://doi.org/10.1007/s10055-016-0283-y.

BONFIGLIO, L.; PIARULLI, A.; OLCESE, U.; ANDRE, P.; ARRIGHI, P.; GEMIGNANI, A. Cortical source of blink-related delta oscillations and their correlation with default mode network activity. **Human Brain Mapping**, v. 34, n. 12, p. 3196-3205, 2013. DOI: https://doi.org/10.1002/hbm.22056.

BORGES, N.; ARAÚJO, M. V.; MARINHO, H.; BARROS, S.; PEREIRA, A. Biofeedback from the inside: Impressões e percepções sobre os processos de simulação durante o treinamento para controle da ansiedade na performance musical. **Opus**, v. 29, p. 1-31, 2023. DOI: https://doi.org/10.20504/opus2023.29.02.

BREMEN, P.; MIDDLEBROOKS, J. C. Weighting of spatial and spectro-temporal cues for auditory scene analysis by human listeners. **PLOS ONE**, v. 8, n. 3, e59815, 2013. https://doi.org/10.1371/journal.pone.0059815

BRINKMANN, F.; LINDAU, A.; VRHOVNIK, M.; WEINZIERL, S. Assessing the authenticity of individual dynamic binaural synthesis. In: **Proceedings of the EAA Joint Symposium on Auralization and Ambisonics**, p. 62–68. Berlin, Germany, 2014.

CALLAN, A. E.; CALLAN, D. E.; ANDO, H. Neural correlates of sound externalization. **NeuroImage**, v. 66, p. 22–27, 2013. DOI: https://doi.org/10.1016/j.neuroimage.2012.10.057.

CASPERS, S.; EICKHOFF, S. B.; GEYER, S.; SCHEPERJANS, F.; MOHLBERG, H.; ZILLES, K.; AMUNTS, K. The human inferior parietal lobule in stereotaxic space. **Brain Structure and Function**, v. 212, n. 6, p. 481–495, 2008. DOI: https://doi.org/10.1007/s00429-008-0195-z.

CASTIGLIONE, C.; RAMPULLO, A.; CARDULLO, S. Self representations and music performance anxiety: A study with professional and amateur musicians. **Europe's Journal of Psychology**, v. 14, n. 4, p. 792–805, 2018. DOI: https://doi.org/10.5964/ejop.v14i4.1554.

CAVANNA, A. E. The precuneus and consciousness. **CNS Spectrums**, v. 12, n. 7, p. 545–552, 2007. DOI: https://doi.org/10.1017/S1092852900021295.

CHAMBERS, C. D.; PAYNE, J. M.; STOKES, M. G.; MATTINGLEY, J. B. Parietal disruption impairs reflexive spatial attention within and between sensory modalities. **Neuropsychologia**, v. 45, n. 7, p. 1715-1724, 2007. DOI: https://doi.org/10.1016/j.neuropsychologia.2007.01.001.

CHENG, C. I.; WAKEFIELD, G. H. Moving sound source synthesis for binaural electroacoustic music using interpolated head-related transfer functions (HRTFs). **Computer Music Journal**, v. 25, n. 4, 2001. DOI: https://doi.org/10.1162/01489260152815297.

CHU, W. Binaural simulation of virtual stage environments for evaluation by the solo violinist. **The Journal of the Acoustical Society of America**, v. 116, n. 4 (Supplement), p. 2485, 2004. DOI: https://doi.org/10.1121/1.4784926.

CLARK, T.; WILLIAMON, A. Evaluation of a mental skills training program for musicians. **Journal of Applied Sport Psychology**, v. 23, n. 3, p. 342–359, 2011. DOI: https://doi.org/10.1080/10413200.2011.574311.

CLARK, T.; WILLIAMON, A. Imagining the music: Methods for assessing musical imagery ability. **Psychology of Music**, v. 40, n. 4, p. 471–493, 2011a. DOI: https://doi.org/10.1177/0305735611401126.

CLARK, T.; WILLIAMON, A. Evaluation of a mental skills training program for musicians. **Journal of Applied Sport Psychology**, v. 23, n. 3, p. 342–359, 2011b. DOI: https://doi.org/10.1080/10413200.2011.574676.

CONNOLY, C.; WILLIAMON, A. Mental skills training. In: WILLIAMON, A. (Ed.). **Musical excellence: Strategies and techniques to enhance performance**. 4. ed. Oxford: Oxford University Press, p. 221–245, 2004.

DANIEL, P. L.; BONAIUTO, J. J.; BESTMANN, S.; ARON, A. R.; LITTLE, S. High precision magnetoencephalography reveals increased right-inferior frontal gyrus beta power during response conflict. **Cortex**, v. 158, p. 127–136, 2023. DOI: https://doi.org/10.1016/j.cortex.2022.10.007.

DANIELSON, N.; GUO, J.; BLUMENFELD, H. The default mode network and altered consciousness in epilepsy. **Behavioural Neurology**, v. 24, n. 1, p. 55–65, 2011. DOI: https://doi.org/10.3233/BEN-2011-0310.

DEIBER, M. P.; SALLARD, E.; LUDWIG, C.; GHEZZI, C.; BARRAL, J.; IBAÑEZ, V. EEG alpha activity reflects motor preparation rather than the mode of action selection. **Frontiers in Integrative Neuroscience**, v. 6, p. 59, 2012. DOI: https://doi.org/10.3389/fnint.2012.00059.

DIPPEL, G.; MÜCKSCHEL, M.; ZIEMSSEN, T.; BESTE, C. Demands on response inhibition processes determine modulations of theta band activity in superior frontal areas. **NeuroImage**, v. 157, p. 575–585, 2017a. DOI: https://doi.org/10.1016/j.neuroimage.2017.06.037.

DIPPEL, G.; MÜCKSCHEL, M.; ZIEMSSEN, T.; BESTE, C. Distinguishing stimulus and response codes in theta oscillations in prefrontal areas during inhibitory control of automated responses. **Human Brain Mapping**, v. 38, n. 11, p. 5681–5690, 2017b. DOI: https://doi.org/10.1002/hbm.23757.

ELY, M. C. Stop performance anxiety! **Music Educators Journal**, v. 78, n. 2, 1991. DOI: https://doi.org/10.2307/3398258.

EMMELKAMP, P. M. G. Behavior therapy with adults. In: LAMBERT, M. J. (Ed.). **Bergin and Garfield's Handbook of Psychotherapy and Behavior Change**. 6. ed. Wiley, p. 343–392, 2013.

EVEREST, F. A.; POHLMANN, K. C. **Master handbook of acoustics**. 7. ed. McGraw-Hill Education, 2022.

FANGER, Y.; PFEUFFER, K.; HELMBRECHT, U.; ALT, F. PIANX – A platform for piano players to alleviate music performance anxiety using mixed reality. **ACM International Conference Proceeding Series**, p. 267–276, 2020. DOI: https://doi.org/10.1145/3428361.3428394.

FERNHOLZ, I.; MUMM, J. L. M.; PLAG, J.; NOERES, K.; ROTTER, G.; WILLICH, S. N.; STRÖHLE, A.; BERGHÖFER, A.; SCHMIDT, A. Performance anxiety in professional musicians: A systematic review on prevalence, risk factors and clinical treatment effects. **Psychological Medicine**, v. 49, n. 14, p. 2287–2306, 2019. DOI: https://doi.org/10.1017/S0033291719001910.

FEUERSTEIN, Joseph F. Monaural versus binaural hearing: Ease of listening, word recognition, and attentional effort. **Ear and Hearing**, v. 13, n. 2, p. 80–86, 1992. https://doi.org/10.1097/00003446-199204000-00003

FINTOR, Edina; ASPÖCK, Lukas; FELS, Janina; SCHLITTMEIER, Sabine J. The role of spatial separation of two talkers' auditory stimuli in the listener's memory of running speech: Listening effort in a non-noisy conversational setting. **International Journal of Audiology**, v. 61, n. 5, p. 371–379, 2022. https://doi.org/10.1080/14992027.2021.1922765

FORMAGGIO, E.; STORTI, S.; CERINI, R.; FIASCHI, A.; MANGANOTTI, P. Brain oscillatory activity during motor imagery in EEG-fMRI coregistration. **Magnetic Resonance Imaging**, v. 28, n. 10, p. 1403–1412, 2010. DOI: https://doi.org/10.1016/j.mri.2010.06.030.

FOX, M. D.; SNYDER, A. Z.; VINCENT, J. L.; CORBETTA, M.; VAN ESSEN, D. C.; RAICHLE, M. E. The human brain is intrinsically organized into dynamic, anticorrelated functional networks. **Proceedings of the National Academy of Sciences**, v. 102, n. 27, p. 9673–9678, 2005. DOI: https://doi.org/10.1073/pnas.0504136102.

GAN, W.-S.; PEKSI, S.; HE, J.; RANJAN, R.; DUY HAI, N.; KUMAR CHAUDHARY, N. Personalized HRTF measurement and 3D audio rendering for AR/VR headsets. **Proceedings of AES 142nd Convention**, 2017.

GORINI, A.; RIVA, G. Virtual reality in anxiety disorders: The past and the future. **Expert Review of Neurotherapeutics**, v. 8, n. 2, p. 215–233, 2008. DOI: https://doi.org/10.1586/14737175.8.2.215.

GRIESINGER, D. H. Using individually equalized playback of binaural recordings from an electronic orchestra to determine the effects of early reflections on proximity, localization, and loudness. **Journal of the Acoustical Society of America**, v. 139, n. 4 (Supplement), 2016. DOI: https://doi.org/10.1121/1.4950196.

GRIJALVA, F.; MARTINI, L. C.; MASIERO, B.; GOLDENSTEIN, S. A recommender system for improving median plane sound localization performance based on a nonlinear representation of HRTFs. **Institute of Electrical and Electronics Engineers Access**, v. 6, p. 28800–28809, 2018. DOI: https://doi.org/10.1109/ACCESS.2018.2832645.

GUILLOT, A.; COLLET, C. Duration of mentally simulated movement: A review. **Journal of Motor Behavior**, v. 37, n. 1, p. 10–20, 2005. DOI: https://doi.org/10.3200/JMBR.37.1.10-20.

HAGAN, K. Spatial audio in online presentations. **Array**, 2022. DOI: https://doi.org/10.25370/array.v20223478.

HARMONY, T. The functional significance of delta oscillations in cognitive processing. **Frontiers in Integrative Neuroscience**, v. 7, p. 83, 2013. DOI: https://doi.org/10.3389/fnint.2013.00083.

HEINE, L.; CORNEYLLIE, A.; GOBERT, F.; LUAUTÉ, J.; LAVANDIER, M.; PERRIN, F. Virtually spatialized sounds enhance auditory processing in healthy participants and patients with a disorder of consciousness. **Scientific Reports**, v. 11, p. 14556, 2021. DOI: https://doi.org/10.1038/s41598-021-93151-6.

HEWITT, M. P. The effects of modeling, self-evaluation, and self-listening on junior high instrumentalists’ music performance and practice attitude. **Journal of Research in Music Education**, v. 49, n. 4, p. 307–322, 2001. DOI: https://doi.org/10.2307/3345614.

HOFFMAN, S. L.; HANRAHAN, S. J. Mental skills for musicians: Managing music performance anxiety and enhancing performance. **Sport, Exercise, and Performance Psychology**, v. 1, n. 1, p. 17–28, 2012. DOI: https://doi.org/10.1037/a0025409.

HOLMES, P. S.; COLLINS, D. J. The PETTLEP approach to motor imagery: A functional equivalence model for sport psychologists. **Journal of Applied Sport Psychology**, v. 13, n. 1, 2001. DOI: https://doi.org/10.1080/10413200109339004.

HYDE, K. L.; PERETZ, I.; ZATORRE, R. J. Evidence for the role of the right auditory cortex in fine pitch resolution. **Neuropsychologia**, v. 46, n. 2, p. 632-639, 2008. DOI: https://doi.org/10.1016/j.neuropsychologia.2007.09.004.

IMMONEN, O.; RUOKONEN, I.; RUISMÄKI, H. Elements of mental training in music. **Procedia – Social and Behavioral Sciences**, v. 45, p. 588–594, 2012. DOI: https://doi.org/10.1016/j.sbspro.2012.06.596.

IOANNOU, C. I.; PEREDA, E.; LINDSEN, J. P.; BHATTACHARYA, J. Electrical brain responses to an auditory illusion and the impact of musical expertise. **PLoS ONE**, v. 10, n. 6, 2015. DOI: https://doi.org/10.1371/journal.pone.0129486.

IRIE, N.; MORIJIRI, Y.; YOSHIE, M. Symptoms of and coping strategies for music performance anxiety through different time periods. **Frontiers in Psychology**, v. 14, 2023. DOI: https://doi.org/10.3389/fpsyg.2023.1138922.

KELLER, P. E. Mental imagery in music performance: Underlying mechanisms and potential benefits. **Annals of the New York Academy of Sciences**, v. 1252, n. 1, 2012. DOI: https://doi.org/10.1111/j.1749-6632.2011.06439.x.

KENDRICK, M. J.; CRAIG, K. D.; LAWSON, D. M.; DAVIDSON, P. O. Cognitive and behavioral therapy for musical-performance anxiety. **Journal of Consulting and Clinical Psychology**, v. 50, n. 3, p. 353–362, 1982. DOI: https://doi.org/10.1037/0022-006X.50.3.353.

KENNY, D. T. **The psychology of music performance anxiety**. Oxford: Oxford University Press, 2011. DOI: https://doi.org/10.1093/acprof:oso/9780199586141.001.0001.

KENNY, D. T.; ARTHEY, S.; ABBASS, A. Intensive short-term dynamic psychotherapy for severe music performance anxiety: Assessment, process, and outcome of psychotherapy with a professional orchestral musician. **Medical Problems of Performing Artists**, v. 29, n. 1, p. 3–7, 2014a. DOI: https://doi.org/10.21091/mppa.2014.1002.

KENNY, D. T.; DAVIS, P.; OATES, J. Music performance anxiety and occupational stress amongst opera chorus artists and their relationship with state and trait anxiety and perfectionism. **Journal of Anxiety Disorders**, v. 18, n. 6, 2004. DOI: https://doi.org/10.1016/j.janxdis.2003.09.004.

KENNY, D. T.; DRISCOLL, T.; ACKERMANN, B. Psychological well-being in professional orchestral musicians in Australia: A descriptive population study. **Psychology of Music**, v. 42, n. 2, p. 210–232, 2014b. DOI: https://doi.org/10.1177/0305735612463950.

KOELEWIJN, Thomas; DE KLUIVER, Hilde; SHINN-CUNNINGHAM, Barbara G.; ZEKVELD, Adriana A.; KRAMER, Sophia E. The pupil response reveals increased listening effort when it is difficult to focus attention. **Hearing Research**, v. 323, p. 81–90, 2015. https://doi.org/10.1016/j.heares.2015.02.004

KOELSCH, S. Toward a neural basis of music perception – a review and updated model. **Frontiers in Psychology**, v. 2, p. 110, 2011. DOI: https://doi.org/10.3389/fpsyg.2011.00110.

KOIZUMI, A.; AMANO, K.; KOMATSU, H. Emotional processing with reduced sensory input: An fMRI study of responses to sounds in the absence of vision. **Neuropsychologia**, v. 131, p. 1–8, 2019. DOI: https://doi.org/10.1016/j.neuropsychologia.2019.04.001.

KOKOTSAKI, D.; DAVIDSON, J. W. Investigating musical performance anxiety among music college singing students: A quantitative analysis. **Music Education Research**, v. 5, n. 1, 2003. DOI: https://doi.org/10.1080/14613800307103.

KOSSLYN, S. M.; BRUNN, J.; CAVE, K. R.; WALLACH, R. W. Individual differences in mental imagery ability: A computational analysis. **Cognition**, v. 18, n. 1–3, p. 195–243, 1984. DOI: https://doi.org/10.1016/0010-0277(84)90025-8.

KRISTEVA, R.; CHAKAROV, V.; SCHULTE-MÖNTING, J.; SPREER, J. Activation of cortical areas in music execution and imagining: A high-resolution EEG study. **NeuroImage**, v. 20, n. 3, 2003. DOI: https://doi.org/10.1016/S1053-8119(03)00422-1.

KRUEGER, Melanie; SCHULTE, Marc René; BRAND, Tobias H.; KOLLMEIER, Birger; RENNIES, Jan. Assessing and modeling spatial release from listening effort in listeners with normal hearing: Reference ranges and effects of noise direction and age. **Trends in Hearing**, v. 26, p. 23312165221129407, 2022. https://doi.org/10.1177/23312165221129407

KUDO, A.; HIGUCHI, H.; HOKARI, H.; SHIMADA, S. Improved method for accurate sound localization. **Acoustical Science and Technology**, v. 27, n. 3, p. 134–137, 2006. DOI: https://doi.org/10.1250/ast.27.134.

LE, A.; VESIA, M.; YAN, X.; CRAWFORD, J. D.; NIEMEIER, M. Parietal area BA7 integrates motor programs for reaching, grasping, and bimanual coordination. **Journal of Neurophysiology**, v. 117, n. 2, p. 624–636, 2017. DOI: https://doi.org/10.1152/jn.00299.2016.

LEWALD, J.; STAEDTGEN, M.; SPARING, R.; MEISTER, I. G. Processing of auditory motion in inferior parietal lobule: Evidence from transcranial magnetic stimulation. **Neuropsychologia**, v. 49, n. 2, p. 209–215, 2011. DOI: https://doi.org/10.1016/j.neuropsychologia.2010.11.038.

LIN, Y. P.; DUANN, J. R.; CHEN, J. H.; JUNG, T. P. Listening to familiar music induces continuous inhibition of alpha/low-beta power. **Journal of Neurophysiology**, v. 128, n. 1, p. 180–192, 2022. DOI: https://doi.org/10.1152/jn.00269.2022.

LITOVSKY, Ruth Y. Spatial release from masking. **Acoustics Today**, v. 8, n. 2, p. 18–25, 2012. https://doi.org/10.1121/1.4729575

MACAFEE, E.; COMEAU, G. Teacher perspective on music performance anxiety: An exploration of coping strategies used by music teachers. **British Journal of Music Education**, v. 40, n. 1, p. 34–53, 2023. DOI: https://doi.org/10.1017/S0265051722000146.

MARTENS, W.; WOSZCZYK, W. Virtual acoustic reproduction of historical spaces for interactive music performance and recording. **The Journal of the Acoustical Society of America**, v. 116, n. 4 (Supplement), p. 2484–2485, 2004. DOI: https://doi.org/10.1121/1.4784922.

MIELKE, S.; COMEAU, G. Developing a literature-based glossary and taxonomy for the study of mental practice in music performance. **Musicae Scientiae**, v. 23, n. 2, p. 196-211, 2019. DOI: https://doi.org/10.1177/1029864917715062.

MRÓZ, B.; ODYA, P.; KOSTEK, B. Creating a remote choir performance recording based on an ambisonic approach. **Applied Sciences**, v. 12, n. 7, p. 3316, 2022. DOI: https://doi.org/10.3390/app12073316.

MULERT, C.; JÄGER, L.; SCHMITT, R.; BUSSFELD, P.; POGARELL, O.; MÖLLER, H. J.; et al. Integration of fMRI and simultaneous EEG: towards a comprehensive understanding of localization and time-course of brain activity in target detection. **NeuroImage**, v. 22, p. 83–94, 2004. DOI: https://doi.org/10.1016/j.neuroimage.2003.10.051.

NORTHOFF, G.; BERMPOHL, F. Cortical midline structures and the self. **Trends in Cognitive Sciences**, v. 8, n. 3, p. 102–107, 2004. DOI: https://doi.org/10.1016/j.tics.2004.01.004.

NORTHOFF, G.; HEINZEL, A.; DE GRECK, M.; BERMPOHL, F.; DOBROWOLNY, H.; PANKSEPP, J. Self-referential processing in our brain—A meta-analysis of imaging studies on the self. **NeuroImage**, v. 31, n. 1, p. 440–457, 2006. DOI: https://doi.org/10.1016/j.neuroimage.2005.12.002.

ORMAN, E. K. Effect of virtual reality graded exposure on heart rate and self-reported anxiety levels of performing saxophonists. **Journal of Research in Music Education**, v. 51, n. 4, p. 302–315, 2003. DOI: https://doi.org/10.2307/3345657.

ORMAN, E. K. Effect of virtual reality graded exposure on anxiety levels of performing musicians: A case study. **Journal of Music Therapy**, v. 41, n. 1, p. 70–78, 2004. DOI: https://doi.org/10.1093/jmt/41.1.70.

OSBORNE, M. S.; GREENE, D. J.; IMMEL, D. T. Managing performance anxiety and improving mental skills in conservatoire students through performance psychology training: a pilot study. **Psychology of Well-Being**, v. 4, n. 1, p. 1–18, 2014. DOI: https://doi.org/10.1186/s13612-014-0018-3.

OWENS, M. E.; BEIDEL, D. C. Can virtual reality effectively elicit distress associated with social anxiety disorder? **Journal of Psychopathology and Behavioral Assessment**, v. 37, n. 2, p. 296–305, 2015. DOI: https://doi.org/10.1007/s10862-014-9454-x.

PAPAGEORGI, I. Typologies of adolescent musicians and experiences of performance anxiety among instrumental learners. **Frontiers in Psychology**, v. 12, Article 645993, 2021. DOI: https://doi.org/10.3389/fpsyg.2021.645993.

PAPAGEORGI, I.; KOPIEZ, R. Psychological and physiological aspects of learning to perform. In: MCPHERSON, G. E.; WELCH, G. F. (Eds.). **The Oxford Handbook of Music Education, Volume 1**. Oxford: Oxford University Press, p. 730–751, 2012. DOI: https://doi.org/10.1093/oxfordhb/9780199730810.013.0044_update_001.

PAPAGEORGI, I.; WELCH, G. F. “A bed of nails”: Professional musicians’ accounts of the experience of performance anxiety from a phenomenological perspective. **Frontiers in Psychology**, v. 11, 605422, 2020. DOI: https://doi.org/10.3389/fpsyg.2020.605422.

PAPAGEORGI, I.; CREECH, A.; WELCH, G. Perceived performance anxiety in advanced musicians specializing in different musical genres. **Psychology of Music**, v. 41, n. 1, p. 18–41, 2011. DOI: https://doi.org/10.1177/0305735611408995.

PARDO, J. V.; PARDO, P. J.; JANER, K. W.; RAICHLE, M. E. The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. **Proceedings of the National Academy of Sciences of the United States of America**, v. 87, n. 1, p. 256–259, 1990. DOI: https://doi.org/10.1073/pnas.87.1.256.

PARREIRAS GONÇALVES, A.; TORCHIA ZANON, F. Ansiedade na performance musical: Uma reflexão sobre o emprego de estratégias de gerenciamento a partir de uma perspectiva da Psicologia do Esporte. **Per Musi**, v. 42, p. 1–19, 2022. DOI: https://doi.org/10.35699/2317-6377.2022.37467.

PASCUAL-MARQUI, R. D. Review of methods for solving the EEG inverse problem. **International Journal of Bioelectromagnetism**, v. 1, n. 1, p. 75–86, 1999. Disponível em: http://www.tut.fi/ijbem.

PASCUAL-MARQUI, R. D. Standardized low resolution brain electromagnetic tomography (sLORETA): Technical details. **Methods & Findings in Experimental & Clinical Pharmacology**, v. 24, Suplemento D, p. 5–12, 2002.

PASCUAL-MARQUI, R. D.; ESSLEN, M.; KOCHI, K.; LEHMANN, D. Functional imaging with low resolution brain electromagnetic tomography (LORETA): Review, new comparisons, and new validation. **Japanese Journal of Clinical Neurophysiology**, v. 24, p. 81–94, 2002.

PASCUAL-MARQUI, R. D.; MICHEL, C. M.; LEHMANN, D. Low resolution electromagnetic tomography: a new method for localizing electrical activity in the brain. **International Journal of Psychophysiology**, v. 18, n. 1, p. 49–65, 1994. DOI: https://doi.org/10.1016/0167-8760(84)90014-X.

PATTERSON, R. D.; UPPENKAMP, S.; JOHNSRUDE, I. S.; GRIFFITHS, T. D. The processing of temporal pitch and melody information in auditory cortex. **Neuron**, v. 36, n. 4, p. 767–776, 2002.

PENFOLD, C.; VIZUETA, N.; TOWNSEND, J.; BOOKHEIMER, S.; ALTSHULER, L. Frontal lobe hypoactivation in medication-free adults with bipolar II depression during response inhibition. **Psychiatry Research: Neuroimaging**, v. 231, n. 3, p. 202–209, 2015. DOI: https://doi.org/10.1016/j.pscychresns.2014.11.005.

PIZZAGALLI, D.; PASCUAL-MARQUI, R. D.; NITSCHKE, J. B.; OAKES, T. R.; LARSON, C. L.; ABERCROMBIE, H. C.; ... DAVIDSON, R. J. Anterior cingulate activity as a predictor of degree of treatment response in major depression: Evidence from brain electrical tomography analysis. **American Journal of Psychiatry**, v. 158, n. 3, p. 405–415, 2001. DOI: https://doi.org/10.1176/appi.ajp.158.3.405.

RABELO, P.; MÁRMORA, C.; RIBEIRO, L. The effectiveness of HRV biofeedback in reducing musical performance anxiety: An initial study. **Psicologia, Saúde & Doenças**, v. 19, n. 2, p. 197–207, 2018. DOI: https://doi.org/10.15309/18psd190203.

RENNIES, J.; KIDD JUNIOR, G. Benefit of binaural listening as revealed by speech intelligibility and listening effort. **The Journal of the Acoustical Society of America**, v. 144, n. 4, p. 2147–2159, 2018. https://doi.org/10.1121/1.5057114

ROMIGH, G. D.; BRUNGART, D.; STERN, R. M.; SIMPSON, B. D. The role of spatial detail in sound-source localization: Impact on HRTF modeling and personalization. **Proceedings of Meetings on Acoustics**, v. 19, p. 050170, 2013. DOI: https://doi.org/10.1121/1.4799575.

RUMSEY, F. **Sound and recording: Applications and theory**. 8. ed. Routledge, 2021. DOI: https://doi.org/10.4324/9781003092919.

RYAN, C. Performance anxiety in young contemporary musicians. **Journal of Popular Music Education**, v. 5, n. 3, p. 313–335, 2021. DOI: https://doi.org/10.1386/jpme_00064_1.

SATO, T.; INUI, T.; SHIBATA, H.; OGAWA, K. Neural representation of space for sound-source localization: An fMRI study. In: YAMAGUCHI, Y. (Ed.). **Advances in cognitive neurodynamics (II): Proceedings of the Second International Conference on Cognitive Neurodynamics**. Springer, p. 357–360, 2011. DOI: https://doi.org/10.1007/978-90-481-9695-1_57.

SCHAEFER, R. S. Mental representations in musical processing and their role in action-perception loops. **Empirical Musicology Review**, v. 9, n. 3–4, p. 161, 2015. DOI: https://doi.org/10.18061/emr.v9i3-4.4291.

SCHAEFER, R. S.; VLEK, R. J.; DESAIN, P. Music perception and imagery in EEG: Alpha band effects of task and stimulus. **International Journal of Psychophysiology**, v. 82, n. 3, p. 254–259, 2011. DOI: https://doi.org/10.1016/j.ijpsycho.2011.09.007.

SCHÄRER, Z.; LINDAU, A. Evaluation of equalization methods for binaural signals. In: **Proceedings of the Audio Engineering Society Convention 126**. Audio Engineering Society, 2009. Disponível em: https://www.aes.org/e-lib/browse.cfm?elib=14963.

SCHREITER, M. L.; CHMIELEWSKI, W.; BESTE, C. Neurophysiological processes and functional neuroanatomical structures underlying proactive effects of emotional conflicts. **NeuroImage**, v. 174, p. 11–21, 2018. DOI: https://doi.org/10.1016/j.neuroimage.2018.03.017.

SEGHIER, M. L. The angular gyrus: Multiple functions and multiple subdivisions. **The Neuroscientist**, v. 19, n. 1, p. 43–61, 2013. DOI: https://doi.org/10.1177/1073858412440596.

SHARMA, N.; JONES, P. S.; CARPENTER, T. A.; BARON, J. C. Mapping the involvement of BA 4a and 4p during motor imagery. **NeuroImage**, v. 41, n. 1, p. 92–99, 2008. DOI: https://doi.org/10.1016/j.neuroimage.2008.02.009.

STECKLOW, M. V.; INFANTOSI, A. F. C.; CAGY, M. Changes in the electroencephalogram alpha band during visual and kinesthetic motor imagery. **Arquivos de Neuro-Psiquiatria**, v. 65, n. 4A, p. 1084–1088, 2007. DOI: https://doi.org/10.1590/S0004-282X2007000600034.

TANAKA, S.; KIRINO, E. Functional connectivity of the precuneus in female university students with long-term musical training. **Frontiers in Human Neuroscience**, v. 10, p. 328, 2016. DOI: https://doi.org/10.3389/fnhum.2016.00328.

TANAKA, S.; KIRINO, E. Right-lateralized enhancement of the auditory cortical network during imagined music performance. **Frontiers in Neuroscience**, v. 16, 2022. DOI: https://doi.org/10.3389/fnins.2022.739858.

TANAKA, S.; HONDA, M.; SADATO, N. Modality-specific cognitive function of medial and lateral human Brodmann area 6. **The Journal of Neuroscience**, v. 25, n. 2, p. 496–501, 2005. DOI: https://doi.org/10.1523/JNEUROSCI.4324-04.2005.

THERY, D. Auralization of virtual concerts: A subjective evaluation comparing binaural and ambisonic rendering. **The Journal of the Acoustical Society of America**, v. 145, n. 3 (Supplement), p. 1890, 2019. DOI: https://doi.org/10.1121/1.5101849.

THURBER, M. R.; BODENHAMER-DAVIS, E.; JOHNSON, M.; CHESKY, K.; CHANDLER, C. K. Effects of heart rate variability coherence biofeedback training and emotional management techniques to decrease music performance anxiety. **Biofeedback**, v. 38, n. 1, p. 28–40, 2010. DOI: https://doi.org/10.5298/1081-5937-38.1.28.

TOTH, A. J.; MCNEILL, E.; HAYES, K.; MORAN, A. Does mental practice still enhance performance? A 24-year follow-up and meta-analytic replication and extension. **Psychology of Sport and Exercise**, v. 48, 101672, 2020. DOI: https://doi.org/10.1016/j.psychsport.2020.101672.

TURCHET, L.; TOMASETTI, M. Immersive networked music performance systems: Identifying latency factors. In: **2023 Immersive and 3D Audio: From Architecture to Automotive (I3DA)**. Institute of Electrical and Electronics Engineers, p. 1–6, 2023. DOI: https://doi.org/10.1109/I3DA57090.2023.10289169.

VITACCO, D.; BRANDEIS, D.; PASCUAL-MARQUI, R.; MARTIN, E. Correspondence of event-related potential tomography and functional magnetic resonance imaging during language processing. **Human Brain Mapping**, v. 17, p. 4–12, 2002. DOI: https://doi.org/10.1002/hbm.10038.

VOLIOTI, G.; WILLIAMON, A. Recordings as learning and practising resources for performance: Exploring attitudes and behaviours of music students and professionals. **Musicae Scientiae**, v. 21, n. 4, p. 499-523, 2016. DOI: https://doi.org/10.1177/1029864916674048.

WELLS, R.; OUTHRED, T.; HEATHERS, J. A. J.; QUINTANA, D. S.; KEMP, A. H. Matter over mind: A randomised-controlled trial of single-session biofeedback training on performance anxiety and heart rate variability in musicians. **PLoS ONE**, v. 7, n. 10, e46597, 2012. DOI: https://doi.org/10.1371/journal.pone.0046597.

WIEDERHOLD, B. K.; WIEDERHOLD, M. D. **Virtual reality therapy for anxiety disorders: Advances in evaluation and treatment**. Washington, DC: American Psychological Association, 2005. DOI: https://doi.org/10.1037/10858-000.

WILLIAMON, A.; AUFEGGER, L.; EIHOLZER, H. Simulating and stimulating performance: Introducing distributed simulation to enhance musical learning and performance. **Frontiers in Psychology**, v. 5, p. 25, 2014. DOI: https://doi.org/10.3389/fpsyg.2014.00025.

YAO, S. N.; CHEN, L. J. HRTF adjustments with audio quality assessments. **Archives of Acoustics**, v. 38, n. 1, 2013. DOI: https://doi.org/10.2478/aoa-2013-0007.

YUAN, H.; LIU, T.; SZARKOWSKI, R.; RIOS, C.; ASHE, J.; HE, B. Negative covariation between task-related responses in alpha/beta-band activity and BOLD in human sensorimotor cortex: An EEG and fMRI study of motor imagery and movements. **NeuroImage**, v. 49, n. 3, p. 2596–2606, 2010. DOI: https://doi.org/10.1016/j.neuroimage.2009.10.028.

ZATORRE, R. J.; BELIN, P. Spectral and temporal processing in human auditory cortex. **Cerebral Cortex**, v. 11, n. 10, p. 946-953, 2001. DOI: https://doi.org/10.1093/cercor/11.10.946.

ZATORRE, R. J.; CHEN, J. L.; PENHUNE, V. B. When the brain plays music: Auditory–motor interactions in music perception and production. **Nature Reviews Neuroscience**, v. 8, n. 7, p. 547-558, 2007. DOI: https://doi.org/10.1038/nrn2152.

ZAVALA, B.; JANG, A.; TROTTA, M.; LUNGU, C. I.; BROWN, P.; ZAGHLOUL, K. A. Cognitive control involves theta power within trials and beta power across trials in the prefrontal-subthalamic network. **Brain**, v. 141, n. 12, p. 3361–3376, 2018. DOI: https://doi.org/10.1093/brain/awy266.

ZHANG, Y.; ZHOU, W.; WANG, S.; ZHOU, Q.; WANG, H.; et al. The roles of subdivisions of human insula in emotion perception and auditory processing. **Cerebral Cortex**, v. 29, n. 2, p. 517–528, 2019. DOI: https://doi.org/10.1093/cercor/bhx334.

ZHOU, Q.; CHENG, R.; YAO, L.; YE, X.; XU, K. Neurofeedback training of alpha relative power improves the performance of motor imagery brain-computer interface. **Frontiers in Human Neuroscience**, v. 16, 831995, 2022. DOI: https://doi.org/10.3389/fnhum.2022.831995.

ZHUKOV, K. Current approaches for management of music performance anxiety: An introductory overview. **Medical Problems of Performing Artists**, v. 34, n. 1, p. 53–60, 2019. DOI: https://doi.org/10.21091/mppa.2019.1008.

ZIELIŃSKI, S. K.; ANTONIUK, P.; LEE, H. Spatial audio scene characterization (SASC): Automatic localization of front-, back-, up-, and down-positioned music ensembles in binaural recordings. **Applied Sciences**, v. 12, n. 3, 2022. DOI: https://doi.org/10.3390/app12031569.

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This study was approved by the Ethics and Deontology Committee of the University of Aveiro (CED-UA), under Opinion no. 01-CED/2019. All procedures complied with institutional ethical standards for research involving human participants, including informed consent and confidentiality assurance.

Authorship contribution

Nery Borges: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Writing – original draft; Writing – review & editing; Project administration. Pedro Bem-Haja:

Conceptualization; Methodology; Formal analysis; Validation; Writing – review & editing. Isaac Raimundo: Conceptualization; Data acquisition; Software; Technical support; Methodology; Writing – review & editing. Helena Marinho: Supervision; Methodology; Writing – review & editing. Marcos Vinícius Araújo: Supervision; Methodology; Writing – review & editing. Anabela Pereira: Supervision; Validation; Writing – review & editing. Isabel M. Santos: Supervision; Formal analysis; Data acquisition; Validation; Writing – review & editing.

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