

REVIEW

Musical plasticity and language skills: recent evidence from cognitive, neurotechnological, and clinical perspectives

Plasticidad musical y habilidades lingüísticas: evidencia reciente desde la perspectiva cognitiva, neurotecnológica y clínica

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ABSTRACT

This study investigates how musical training enhances verbal fluency by integrating cognitive, linguistic, and neuroscientific evidence. Through a multimodal review of recent literature, it describes the mechanisms linking musical practice to improvements in auditory discrimination, phonological memory, executive control, and lexical retrieval. The analysis also highlights the contribution of technologies such as EEG, fMRI, tDCS, and brain-computer interfaces, which reveal shared neural networks between music and language and characterize neuroplastic changes driven by musical experience. Findings show that music strengthens essential linguistic skills and supports clinical interventions for populations with aphasia, cognitive decline, or neurodevelopmental disorders. Overall, musical training and neurotechnology emerge as complementary tools for enhancing language abilities and promoting neurocognitive rehabilitation.

Keywords: Musical Training; Verbal Fluency; Neuroplasticity; Neurotechnology; Language; Cognition.

RESUMEN

Este estudio examina cómo el entrenamiento musical influye en la fluidez verbal mediante la integración de evidencia cognitiva, lingüística y neurocientífica. A partir de una revisión multimodal de literatura reciente, se describen los mecanismos que conectan la práctica musical con mejoras en discriminación auditiva, memoria fonológica, control ejecutivo y recuperación léxica. Asimismo, se analizan los aportes de tecnologías como EEG, fMRI, tDCS e interfaces cerebro-computadora, que permiten identificar redes neurales compartidas entre música y lenguaje y caracterizar cambios de neuroplasticidad asociados al entrenamiento musical. Los hallazgos demuestran que la música potencia habilidades lingüísticas esenciales y apoya intervenciones clínicas en poblaciones con afasia, deterioro cognitivo o trastornos del neurodesarrollo. En conjunto, la evidencia posiciona al entrenamiento musical y a la neurotecnología como herramientas complementarias para fortalecer el lenguaje y favorecer la rehabilitación neurocognitiva.

Palabras clave: Entrenamiento Musical; Fluidez Verbal; Neuroplasticidad; Neurotecnología; Lenguaje; Cognición.

INTRODUCTION

The relationship between music and the brain has been one of the most fertile fields in contemporary cognitive neuroscience. Over the past two decades, advances in neurotechnology—especially in neuroimaging, electrophysiology, and neuromodulation—have enabled us to understand more precisely how musical practice, sound perception, and artistic performance involve dynamic, hierarchical, and integrated brain networks. Traditionally, the study of musical processing was limited to behavioral or psychophysical approaches; however, the development of tools such as functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), electroencephalography (EEG), and noninvasive brain stimulation has transformed this field, allowing us to evaluate not only which areas are activated during musical performance, but also how they reorganize, how they connect, and how they change with experience.^(1,2,3,4,5)

Music is a multisensory and multimodal stimulus that requires the integration of auditory, motor, cognitive, emotional, and attentional mechanisms. Playing an instrument, singing, improvising, or even listening to music involves the participation of frontotemporal networks, subcortical structures, motor cortex, prefrontal areas, and limbic circuits. This complexity makes musical processing a privileged window for studying brain plasticity and the adaptive capacities of the human nervous system. In this sense, neurotechnology has established itself as the main way to observe the electrical and hemodynamic patterns that accompany musical practice, understand cognitive transfer to domains such as language, and measure the effects of musical training in both healthy and clinical populations.^(6,7,8,9,10,11)

For example, fMRI has shown that sustained musical practice increases activation in areas associated with working memory, motor planning, and auditory discrimination. EEG contributes to the understanding of fine temporal processes, such as tonal error detection, temporal synchrony with rhythmic stimuli, and ERP components related to auditory prediction, attention, and decision-making. At the same time, emerging technologies such as brain-computer interfaces (BCI) and neurofeedback have begun to be integrated into research aimed at understanding neural self-regulation during musical tasks or training specific patterns of cortical activation.^(12,13,14,15,16)

One of the most widely studied benefits of musical training is related to its ability to promote plasticity and enhance non-musical cognitive skills, such as verbal memory, attention, linguistic fluency, phonological discrimination, and speech perception in noise. Neurotechnology has been key in demonstrating that these transfer effects are not coincidental, but rather the result of functional overlap between networks dedicated to musical processing and linguistic networks. In fact, it is now accepted that music and language share mechanisms of temporal analysis, hierarchical processing, prediction, phonological encoding, and articulatory motor control, which is reflected in multiple fMRI and MEG studies.^(17,18,19,20,21,22,23,24)

In addition, studies of expert musicians have revealed significant structural and functional differences compared with those of non-musicians. These include greater gray matter volume in auditory and motor areas, greater cortical thickness in frontal regions, and greater interhemispheric structural connectivity. These adaptations are considered indicators of experience-dependent neuroplasticity and provide a solid basis for understanding how musical training can be used in therapeutic interventions.^(25,26,27,28,29,30,31)

In recent years, neurotechnology has also enabled the study of the benefits of music in clinical populations, including post-stroke patients with aphasia, individuals with neurodevelopmental disorders, patients with cognitive impairment, and children and adults with attention disorders or hearing difficulties. Interventions combining musical stimulation with tDCS, TMS, or neurofeedback have shown promising results in language rehabilitation and executive function.^(32,33,34,35,36,37,38)

Building on these advances, this review examines the scientific literature on the intersection of music and neurotechnology to identify the neural mechanisms involved, the cognitive benefits of musical training, and emerging clinical applications. To this end, a broad search strategy was adopted that integrates studies of neuroimaging, EEG, MEG, neuromodulation, and computational technologies related to music and musical performance. This review seeks to provide a rigorous and up-to-date synthesis of how neurotechnology has broadened our understanding of the musical brain and opened up new possibilities in neurorehabilitation, music education, and advanced cognitive assessment.^(39,40,41,42,43,44,45,46,47)

METHOD

This study was developed as a narrative review with a qualitative and analytical-interpretative approach, aimed at examining the available scientific literature on neurotechnology applied to the study of music, auditory perception, and musical training. The methodological process was designed around a reproducible search strategy using MeSH descriptors, free keywords, and Boolean operators to obtain a broad and representative corpus of contemporary research.

The search was conducted in the PubMed database, which was selected for its relevance to the biomedical and neuroscientific fields. A broad search strategy was used to ensure the inclusion of studies with different neurotechnological approaches related to music. The final equation used was as follows: (“Music”[MeSH

Terms] OR music* OR “musical training” OR “music performance”) AND (“Neuroimaging”[MeSH Terms] OR EEG OR MEG OR fMRI OR TMS OR tDCS OR neurotechnolog* OR neurofeedback OR “brain-computer interface” OR BCI))

This strategy combined official descriptors with free terms to cover research that was not necessarily indexed with the corresponding MeSH tags. Boolean OR operators allowed synonyms and conceptually equivalent terms to be grouped, while the AND operator ensured that the articles retrieved addressed both music and neurotechnology simultaneously.

Human species filters and articles published in the last ten years (2015–2025) were applied to ensure temporal relevance and clinical relevance. No restrictions were placed on the type of study, given the multiple methodological modalities in musical neuroscience: clinical trials, cross-sectional studies, experimental research with EEG or fMRI, longitudinal studies, and systematic reviews. Articles in English and Spanish were also accepted.

The screening process was carried out in two stages. In the first stage, titles and abstracts were reviewed to exclude articles not related to music, neurotechnology, or auditory cognition. In the second phase, the full text was examined to evaluate methodological quality, clarity of results, and thematic relevance. Studies were included if they integrated at least one neuroscientific technology (EEG, MEG, fMRI, TMS, tDCS, neurofeedback, or BCI) and evaluated musical perception, musical performance, musical training, or associated cognitive correlates.

To ensure interpretive validity, the extracted information was organized into an analytical matrix that considered: type of study, population, sample, methodology, variables studied, neurotechnology used, primary findings, and clinical applications. This procedure enabled comparisons of results, identification of recurring patterns, and recognition of theoretical gaps.

A qualitative analytical approach was used to integrate the findings into a coherent narrative that reflected current trends in musical neuroscience. This methodology enabled us to synthesize scattered information and highlight the importance of neurotechnology in understanding the auditory, cognitive, and motor mechanisms underlying musical practice.

RESULTS AND DISCUSSION

The results of the present review consistently show that musical training significantly impacts cognitive and linguistic processes underlying verbal fluency.^(48,49,50,51,52) The convergence of behavioral, neurophysiological, and neuroimaging studies shows that musical practice strengthens auditory, executive, and mnemonic mechanisms that are also essential for language processing. This functional overlap constitutes one of the most solid theoretical pillars for explaining the transfer effects between music and verbal skills.^(53,54,55,56,57,58)

A cross-cutting finding in the reviewed literature is the relevance of acceptable auditory discrimination and temporal analysis, processes that are vastly improved in musicians and individuals exposed to structured musical interventions. These skills allow for more accurate phonological representation, facilitating speech segmentation, phoneme recognition, and agile lexical retrieval. Electrophysiological evidence—especially EEG studies—supports this interpretation by showing more efficient patterns of neural synchronization, greater rhythmic stability, and better response to complex auditory stimuli in individuals with musical training.^(59,60,61,62,63,64)

The studies reviewed also highlight the close relationship between music and executive functions, particularly inhibitory control, working memory, and sustained attention. These functions are fundamental to producing verbal fluency, as they allow for filtering irrelevant information, maintaining semantic search routes in temporary memory, and quickly selecting appropriate words within a conceptual field. In this sense, musical training—especially that involving reading, improvisation, or rhythmic performance—appears to strengthen prefrontal networks that subsequently contribute to linguistic performance.^(65,66,67,68,69,70,71)

Neurotechnology provides crucial evidence for the neural mechanisms underlying this transfer. The use of fMRI, MEG, tDCS, and neurofeedback paradigms has identified shared networks between music and language, including frontotemporal regions, superior auditory areas, supplementary motor cortex, and limbic structures. These findings support the idea that music activates hierarchical systems similar to those of language, which facilitates functional reorganization in clinical contexts, such as post-stroke rehabilitation or neurodevelopmental disorders. In fact, interventions based on singing and rhythm have been shown to promote compensatory neuroplasticity, especially in the right hemisphere, thereby improving language skills when left networks are compromised.^(72,73,74,75,76)

Despite the strength of the evidence, limitations have also been identified. Many studies have small samples, heterogeneous designs, and variability in the types of musical stimuli used, making it challenging to establish standardized protocols. Furthermore, most studies focus on adult populations and Western contexts, leaving a significant gap in our understanding of how cultural factors, early age, or different types of musical training influence outcomes. The integration of emerging technologies, such as adaptive BCIs or musical neurofeedback, opens up new opportunities, but still requires systematic validation for clinical application.^(77,78,79)

Table 1.*Analysis of studies on the subject*

Study title	Year	Type of study	Methodology and population	Main results	Practical implications (≥150 words)
Neural entrainment to the beat and working memory predict sensorimotor synchronization skills ⁽¹⁾	2025	Correlational experimental study with EEG	Healthy young adults. EEG (steady-state evoked potentials, SS-EPs) was recorded while participants passively listened to syncopated and non-syncopated rhythmic sequences. They then performed a finger-tapping task to assess the accuracy and consistency of synchronization, and a counting span task to estimate working memory. SS-EPs were analyzed at pulse-related frequencies (1.25 Hz and harmonics) and their relationship to behavioral performance and musical background.	Precise neural tracking of the rhythm was observed (increased SS-EPs at pulse frequencies), evidencing neural entrainment to rhythmic patterns. However, greater entrainment to non-syncopated rhythms was associated with greater tapping variability and lower synchronization accuracy. In contrast, working memory positively predicted tapping consistency. Musical background was not a robust predictor of performance, suggesting that cognitive resources such as working memory play a more decisive role than simple accumulated musical experience.	This study qualifies the idea that “the stronger the entrainment, the better the synchronization.” In contexts of musical training and rhythmic rehabilitation (e.g., in movement disorders or speech and language therapy), the results suggest that eliciting strong automatic coupling to the beat is not enough; cognitive control and flexibility are also key. Working memory is a critical resource that sustains tapping stability when rhythmic patterns are more complex or require constant adjustments. In clinical practice, this opens the door to programs that integrate rhythmic training with tasks that stimulate working memory (e.g., rhythmic sequences that must be remembered and varied), especially in populations with mild cognitive impairment or Developmental disorders. In music education, it indicates that rhythmic work should be accompanied by exercises that involve planning, updating, and monitoring (not just automatic repetition), since over-reliance on “fixed” pulse predictions can reduce adaptation when the rhythm becomes more complex.

Analgesic effects and 2025 R a n d o m i z e d , 90 healthy young adults, assigned The MSVR condition significantly This work supports the use of immersive digital neural oscillatory parallel clinical trial to three single-session conditions: increased pain thresholds ($\approx 15\%$ – interventions based on music and movement mechanisms of music- with EEG (1) music-synchronized virtual 25% vs. control) and improved as a non-pharmacological adjunct in pain synchronized virtual reality (MSVR: rhythmic visuomotor CPM efficiency, outperforming management. In clinical settings (chronic reality intervention(2) tasks with music), (2) conventional conventional VR and the non- musculoskeletal pain, invasive procedures, post- immersive 2D condition. MSVR also surgical rehabilitation), a VR environment in which Pressure reduced the perceived intensity of the patient performs movements synchronized pain thresholds in various cold pain and was associated with with rhythmic music could help increase the pain muscle groups, conditioned pain a sustained increase in parietal threshold, enhance the efficacy of endogenous modulation (CPM) efficiency alpha power, a pattern related inhibitory mechanisms, and reduce the need with cold stimulus, pain intensity to analgesia and descending for analgesics. The musical component is not and dislike, and EEG oscillations pain modulation. Participants ornamental: audiomotor synchronization and increased alpha power suggest a specific (theta, alpha, beta, gamma) were reported a greater sense of im nd and increased alpha power suggest a specific measured before, during, and after immersion and realism with MSVR sensorimotor integration mechanism that modulates the pain experience. From a music the intervention. than with VR without music. therapy perspective, the study supports the idea that music + structured rhythmic movement has greater analgesic potential than passive music. This can be extrapolated to physical therapy, neurological rehabilitation, and sports training programs, by designing protocols in which music sets the tempo for exercises, EEG responses are recorded, and rhythms are customized to maximize analgesic and immersive effects.

Synergistic, multi-level understanding of psychedelics: three systematic reviews and meta-analyses of their pharmacology, neuroimaging, and phenomenology⁽³⁾ 2024 Three systematic reviews with meta-analyses

Studies on LSD, psilocybin, and DMT were systematically reviewed at three levels: (1) subjective experience (d altered state scales), (2) functional neuroimaging (fMRI, PET), and (3) molecular pharmacology of 5-HT receptors and other targets. Includes healthy adults and patients in clinical and experimental settings. Functional connectivity patterns between brain networks, pharmacological profiles, and intracellular signaling were meta-analyzed.

At the phenomenological level, medium-high doses of LSD produce higher scores of “visionary restructuralization” than psilocybin. In neuroimaging, psychedelics increase connectivity between networks and decrease connectivity within them, consistent with a “high entropy brain.” At the pharmacological level, LSD shows greater efficacy in generating inositol phosphate via 5-HT2A than DMT or psilocin, although selectivity for 5-HT2A/2C/ D2 versus 5-HT1A is relatively similar between compounds. High heterogeneity and risk of bias are noted in the included studies.

Although the article is not musical per se, it has direct implications for psychedelic interventions where music is a central component of the therapeutic setting. Increased connectivity between networks and greater “brain entropy” suggest that during the psychedelic state, music can be processed more freely, less constrained by rigid internal models, facilitating profound emotional reframing. For clinical practice, this implies that the selection of music, its structure, intensity, and progression must be carefully designed to guide the experience without overloading the salience network or generating anxiety. Likewise, pharmacological findings help explain why certain compounds are associated with more visual or more introspective experiences, which can be modulated by appropriate music. At the level of music-brain research, these meta-analyses justify the simultaneous integration of pharmacological, connectivity-, and musical experience measures to understand how music “channels” or modulates the effects of psychedelics, especially in the treatment of depression, addiction, and trauma.

Dissociable effects of psilocybin and escitalopram for depression on processing of musical surprises⁽⁴⁾ 2025 Secondary analysis of randomized clinical trial with fMRI in TDM

Forty-one patients with major depressive disorder were randomized to psilocybin therapy (PT; n=22) or escitalopram (n=19). Pre- and post-treatment fMRI scans were performed over 6 weeks while participants listened to music, and “musical surprises” (violations of expectation) were modeled. Emotional ratings (valence/activation), anhedonia, and depressive symptoms were recorded, as were brain activation associated with surprise vs. control events.

Psilocybin reduced anhedonia more than escitalopram. Escitalopram tended to attenuate affective responses linked to musical surprises, while psilocybin maintained them. At the neural level, escitalopram was associated with greater activation in memory and emotional processing regions in response to surprises. At the same time, PT showed decreases in vmPFC and the angular gyrus, and relative increases in sensory areas, suggesting a change in how musical prediction errors and reward are encoded.

This study offers a refined model for understanding how different treatments modify musical experience and the ability to feel pleasure. For clinical practice, the preservation of hedonic and surprise responses with psilocybin suggests that this therapeutic option could avoid the emotional blunting frequently reported with SSRIs. Music thus becomes a sensitive “probe” for assessing changes in the reward system and in the encoding of expectations. For music therapy, this supports the use of structured music with moments of controlled surprise to explore emotional reactivity before and after her pharmacological interventions. In neurotechnological research, the musical surprise paradigm can be used to study prediction errors in other disorders (addictions, treatment-resistant anhedonia, and schizophrenia) by using music as a complex yet ecologically valid stimulus. It also raises the possibility of adjusting music in real time (e.g., using BCI or algorithms) to optimally stimulate reward networks without generating overload.

Mindfulness meditation 2024 R a n d o m i z e d 40 young adults with no previous A significant increase in theta In practice, these results help differentiate the is associated with global controlled trial meditation experience. EEG was was observed between sessions neurophysiological effects of meditation from EEG spectral changes in (mindfulness vs. recorded at rest and during in both groups, both at rest simply listening to music. For clinics managing theta, alpha, and beta music) with EEG mindfulness meditation (breathing) and during meditation. The stress, anxiety, or pain, brief mindfulness in two sessions separated by 6 alpha band was reduced during programs can modulate the theta, alpha, and weeks. After the first session, meditation compared to rest. Still, beta bands in a relatively specific way, promoting participants were assigned to daily in the mindfulness group, this states of relaxed alertness and attentional mindfulness practice or listening reduction was more minor in the regulation. Classical music also produces to classical music as an active second session, suggesting a trait changes, but with a different profile. For control. Longitudinal changes effect (greater pattern stability). interventions that combine music and meditation in the amplitudes of the delta, Similar patterns were found in (e.g., in rehabilitation or workplace wellness theta, alpha, and beta bands were beta, with it being more stable programs), the findings suggest using music analyzed across states and groups. in the mindfulness group than to facilitate entry into a state of calm, followed in the music group. There were by introducing formal mindfulness practices to no robust changes in delta or consolidate changes in attentional networks. gamma. The results support the From a neurotechnology perspective, these idea that meditation alters the spectral patterns offer targets for developing overall organization of oscillations neurofeedback protocols that train users to underlying attention and cognitive reproduce meditation-like states, with possible control. applications in ADHD, anxiety disorders, athletic performance, and cognitive optimization.

Mindfulness meditation 2025 R a n d o m i z e d Forty-two young adults were Meditation reduced alpha This study refines the understanding of the alters alpha amplitude controlled trial evaluated in two EEG sessions with amplitude during practice effects of mindfulness, showing that meditation without affecting (mindfulness vs. eyes closed (rest vs. meditation) compared to rest. After the primarily modifies alpha patterns associated arousal⁽⁶⁾ music) with EEG + separated by 6 weeks. Between training period, in the mindfulness with attention mechanisms, rather than global skin conductance sessions, participants performed group, this decrease in alpha physiological arousal. In clinical practice, it 15 minutes daily of mindfulness during meditation was more minor suggests that mindfulness may be beneficial for of breathing or listening to music (primarily in frontal and posterior improving focus and sustained attention (e.g., (active control). Alpha amplitude regions), interpreted as a trait in anxiety, chronic pain, ADHD), regardless of (8–13 Hz) in frontal and posterior change in attentional networks. significant changes in autonomic activation. In regions, and skin conductance SCL did not differ between states interventions that use music as a relaxation tool, (SCL), were analyzed as indices of but decreased over time in both the results indicate that, although music reduces global alpha and SCL. groups, indicating a general arousal over time, it does not reproduce the reduction in arousal. No strong specific pattern of alpha modulation observed relationships were found between with mindfulness. This encourages the design of mixed programs in which music serves as a gateway and meditation as a central practice. In neurotechnological research, the relatively subtle but consistent modulation of frontal/posterior alpha may serve as a biomarker for monitoring adherence to and response to mindfulness programs, as well as a target for neurofeedback training aimed at improving attentional control and emotional regulation.

The major-minor mode dichotomy in music perception⁽⁷⁾ 2025

Systematic review + meta-analysis of 70 experimental studies on major and minor mode (behavioral, EEG, perception; meta-analysis of 37 that included sufficient data (behavioral, EEG, and neuroimaging). Focused mainly on Western listeners, analyzing mode effects on emotions, aesthetic judgments, and neural responses, as well as the role of musical expertise, age, cultural context, and clinical variables.

Review of 70 experimental studies on major and minor mode dichotomy is associated with consistent differences in emotional responses, but strongly modulated by individual factors (musical experience, culture, age, affective state). Meta-analyses show average effects on valence judgments and differential brain activations between major and minor modes, although the previous literature was contradictory. The authors propose an integrative model (“Major-Minor Mode(I)”) that incorporates acoustic, contextual, and individual variables to explain the mode-emotion relationship.

It is confirmed that the central/minor dichotomy is associated with consistent differences in emotional responses, but strongly modulated by individual factors (musical experience, culture, age, affective state). Meta-analyses show average effects on valence judgments and differential brain activations between major and minor modes, although the previous literature was contradictory. The authors propose an integrative model (“Major-Minor Mode(I)”) that incorporates acoustic, contextual, EEG/neuroimaging correlates and individual variables to explain the mode-emotion relationship.

The implications for musical and clinical practice are obvious: one cannot rigidly assume that “major mode = happy” and “minor mode = sad” for all people and contexts. In music therapy, the design of playlists to modulate mood (activate, contain, accompany grief, etc.) must be based on each patient’s actual response, considering their musical and cultural history. The proposed model offers a conceptual framework for investigating, for example, why some patients with depression respond better to music in minor mode (identification and catharsis) while others need primary mode. For musical neurotechnology (e.g., adaptive systems that change mode based on physiological state), the EEG/neuroimaging correlates summarized here provide markers for developing algorithms that adjust mode in real time. In music education, the review invites a teaching mode not only as a theoretical label but also as an expressive tool whose emotional interpretation is plastic and contextual, thereby promoting a more critical and flexible understanding of tonality.

Neural foundations of creativity: A voxel-based meta-analysis of the activations and deactivations underlying creativity across linguistic, musical, and visual domains

2025

Voxel-based meta-analysis (fMRI)

Seed-based mapping meta-analysis based on 43 neuroimaging studies (1,118 participants) on creativity in linguistic, musical, and visual tasks. Activations and deactivations associated with general creative tasks (e.g., Alternative Task) and specific tasks (musical improvisation, creative verbal production, visuospatial tasks) were analyzed, differentiating between domain- and domain-specific mechanisms.

Domain-general mechanisms of creativity (working memory, integration of distant concepts, inhibition of conventional responses, interoception, internal goal orientation, mind-wandering, Uses motor simulation) and domain-specific mechanisms were identified. Linguistic creativity tasks can simultaneously activate executive control networks, default mode networks, and audiomotor systems, promoting processes of identity reconstruction, sense of agency, and spontaneous expression; intrinsic motivation after brain damage. From visual creativity depends on a neurotechnology perspective, understanding inhibiting habitual visuospatial associations. It is noted that the with creativity enables us to design AUT better captures novelty than neurofeedback paradigms to train states elaborative processes, thereby conducive to idea generation (e.g., reducing limiting its generalizability to hyperactivation in control networks to enhance other forms of creativity. creative fluency). Furthermore, by integrating linguistic, musical, and visual creativity, the work supports intermodal interventions (music + narrative + visual art) as a vibrant approach in therapeutic, educational, and active aging contexts.

Evaluating cognitive decline detection in aging populations with single-channel EEG features based on two studies and meta-analysis	2025 Two observational studies + meta-analysis	237 older adults in total. Study 1: 80 older adults, divided into a healthy group (MMSE > 28) and an "at-risk" group (MMSE 24–27); single-channel EEG was used during cognitive load tasks, applying Lasso and Elastic Net models to relate EEG features to MMSE scores. Study 2: 77 older adults were divided into healthy, at-risk of mild impairment, dementia) and between Bands (including gamma) and an ML biomarker (A0) were analyzed. The meta-analysis also included other data and young controls.	Penalized regression models with single-channel EEG achieved a sensitivity of 0,90 and a specificity of 0,57 for detecting cognitive impairment (as measured by the MMSE) in the first study. In the second study, significant differences were observed between groups (healthy, at risk, dementia) and between levels of cognitive load, especially in the gamma band and in the A0 biomarker. The meta-analysis confirmed significant associations between EEG markers (including A0) and MMSE and MoCA scores. The study concludes that single-channel EEG, combined with ML, can serve as an accessible tool for the early detection of cognitive impairment.	This study is relevant to the intersection between neurotechnology, aging, and, indirectly, musical interventions. Although it is not a musical study, it opens up the possibility of using simple, portable EEG configurations to monitor cognitive changes in older adults, for example, before and after music training programs, music therapy, or auditory stimulation. From a medical practice perspective, low-cost, easy-to-implement tools could complement traditional neuropsychological assessments, helping to identify early on those who will benefit from cognitive or sensory interventions. For research on music and aging, these EEG biomarkers could be used to assess whether participation in musical activities (such as instrument lessons, choirs, and active listening programs) contributes to maintaining or improving MMSE/MoCA scores. This would facilitate longitudinal studies where the impact of music on brain aging can be objectively quantified using a minimal EEG, accessible in community settings, day centers, and nursing homes.
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Quality of life in older adults is enhanced by piano practice: Results from a randomized controlled trial⁽⁸⁾

R a n d o m i z e d, One hundred fifty-six healthy older adults were randomly assigned to two groups: piano practice vs. music listening. Both attended weekly 60-minute sessions for 12 months. Quality of life (QoL) was assessed with WHOQOL-BREF at 5 time points (0, 6, 12, 18, and 24 months). In a subsample, T1 MRI images were obtained to estimate gray matter volume in regions of the reward circuit (amygdala, globus pallidus, etc.).

Piano practice, compared with the listening group, was associated with significant improvements in the psychological, physical, and environmental domains of QoL (positive log-odds with credible intervals that did not include 0). The social domain showed no robust differences between groups. Changes in quality of life were positively correlated with increases in bilateral amygdala volume. They left the globus pallidus, suggesting that prolonged instrumental practice promotes neuroplasticity in reward circuits linked to subjective well-being.

This study provides causal evidence that learning and practicing a keyboard instrument in old age is not only an enjoyable recreational activity, but also an intervention with a measurable impact on quality of life and brain structure. For gerontology and family medicine, it supports the inclusion of music education programs (piano or other instruments) as part of healthy aging strategies, beyond physical exercise and classic cognitive stimulation. The combination of fine motor training, music reading, memory, bimanual coordination, and emotional expression can act as a “cognitive and affective multivitamin” for the aging brain. At the policy level, it suggests that offering subsidized instrument lessons in day centers or senior universities may be a cost-effective investment in improving well-being, reducing subthreshold depressive symptoms, and encouraging social participation. For music therapists and educators, it highlights the difference between passive listening and active practice. Although both are valuable, active engagement with the instrument appears to have added value for QoL and reward circuit plasticity, which should be taken into account when designing programs based on each older adult’s level of functionality and motivation.

Recovery effects of 2025 C r o s s - o v e r Fifteen healthy male university Slow-tempo preferred music In the fields of sports, rehabilitation, and slow-tempo preferred experimental trial students (~21 years old) performed was associated with a significant cardiovascular health, this study suggests that music on brain activity, physiological and psychological responses following high-intensity interval exercise in healthy male adults⁽⁹⁾ a high-intensity interval exercise increase in TBR in multiple cortical selecting slow music preferred by the subject is a simple yet powerful tool for optimizing recovery after high-intensity training. Changes in TBR and P300 indicate a transition to a state of relaxed attention and more efficient processing, which can promote motor consolidation, autonomic regulation, and the perception of post-exercise well-being. In practice, coaches and physical therapists can recommend that athletes create playlists of slow music they really like for the post-exercise phase, rather than using random music or none at all. Furthermore, in cardiac or metabolic rehabilitation programs, where intense exercise can be stressful, introducing preferred music into the recovery phase could improve adherence and tolerability, reducing the perception of discomfort and hormonal impact (cortisol). From a musical neuroscience perspective, the study reinforces the importance of tempo and personal preference in modulating objective markers of recovery, which can be integrated with biofeedback (HR, EEG) to personalize interventions based on real-time responses.

The Impact of Listening to Music During MRI-Fusion Prostate Biopsy Procedures on Pain and Anxiety Levels: A Randomized Controlled Trial⁽¹⁰⁾ 2025

R a n d o m i z e d , 149 patients undergoing combined prospective clinical prostate biopsy (MpMRI-guided biopsy + 12-cylinder systematic biopsy) at a tertiary hospital. They were assigned to two groups: listening to classical music through headphones during the procedure (n≈78) vs. headphones without music (noise cancellation, control; n≈71). Pain (VAS scale) and trait anxiety (STAI-S, STAI-T) were measured shortly after the procedure.

The group that listened to music reported significantly lower pain (median VAS ~3,6 vs. 5,4 in the control group) and lower levels of state anxiety (STAI-S ~38 vs. 44), with statistically significant differences. There were no robust differences in trait anxiety (STAI-T), as expected, given its greater stability. No adverse effects associated with the music intervention were reported.

This study provides solid evidence that is easily transferable to urological clinical practice: incorporating music during image-guided prostate biopsies reduces both perceived pain and acute anxiety without adding significant risks or costs. In practice, services can implement simple protocols in which the patient chooses from several music options (not necessarily only classical music) and is provided with appropriate headphones. Music functions here as an attentional and emotional modulator, diverting focus from the invasive experience and activating reward and emotional regulation systems. Beyond urology, these results support the use of music in other painful procedures (endoscopies, radiological interventions, complex treatments), which can improve the patient experience, reduce the need for light sedation or additional analgesics, and increase overall satisfaction. From a music therapy perspective, the study supports the use of even very brief and passive musical interventions in high-demand medical settings, emphasizing that the simple act of accompanying a procedure with carefully selected music already produces clinically significant effects.

Distinct neural bases of 2025 ALE meta-analysis 34 visual art experiments (692 Visual aesthetic experiences This work has important implications for the visual art- and music- of fMRI studies participants) and 34 music preferentially activate the frontal design of aesthetic interventions in clinical and induced aesthetic + connectivity experiments (718 participants). An pole, ventromedial prefrontal educational contexts. It suggests that music experiences analysis ALE meta-analysis was performed cortex, and inferior frontal insula. and visual art are not interchangeable from a on activations associated with At the same time, music induces brain perspective: music tends to engage the aesthetic experiences (pleasure, stronger activation of the bilateral temporal auditory and striatal reward circuits aesthetic appreciation) relative superior temporal cortex and more, while visual art more strongly mobilizes to control conditions. Resting- striatal regions linked to reward. frontal networks associated with evaluation, state functional connectivity Connectivity analyses show meaning, and self-reference. In neurocognitive (RSFC), meta-analytic connectivity partly differentiated networks rehabilitation programs, this suggests that (MACM), and activation network for each domain, supporting a music may be particularly useful for activating modeling (ANM) analyses were domain-specific view of aesthetic reward systems in patients with apathy or added to characterize the networks appreciation and challenging anhedonia, thereby promoting motivation underlying aesthetic experiences in the idea of a single “common and engagement in therapy. At the same time, both domains. neural currency” for all aesthetic visual art may be better suited to tasks involving pleasures. reflection and the narrative restructuring of the self. For music therapists, the study reinforces the specific value of music as a powerful affective tool, not simply a “sound version” of any pleasant stimulus. At the neurotechnology level, differential network mapping provides guidelines for designing fMRI/EEG paradigms that discriminate responses to music vs. art, as well as for possible BCI applications that decode aesthetic states and dynamically adjust stimulus type according to the user’s emotional or motivational regulation needs.

Functional neuroplasticity in chronic post-stroke aphasia following a singing intervention in a crossover randomized trial⁽¹¹⁾ | 2025

Randomized crossover clinical trial with fMRI

Nineteen patients with chronic post-stroke aphasia were assigned to two sequences: 4 months of group singing-based intervention followed by standard care, or the reverse order (crossover design). fMRI showed greater activation in the right postcentral gyrus and right posterior superior temporal gyrus. Increased activation in the right pSTG correlated with improvements in naming, indicating that the right hemisphere can support linguistic functions after damage to left networks.

After the intervention, patients produced more correct syllables in the trained song and performed better on the trained song than on the untrained song. Verbal learning of songs and when singing the trained song naming were assessed; fMRI was performed while patients sang two new songs (one trained during the intervention and one untrained). Pre-post changes in correct syllable production and activation of regions of the "singing network," especially in the right STG, were analyzed.

This study provides direct evidence of functional neuroplasticity induced by singing-based interventions in chronic aphasia, a stage where recovery potential is often assumed to be limited. In clinical practice in neurology and speech therapy, it reinforces the use of singing programs (therapeutic choirs, melodic singing) as a complement to language rehabilitation, focusing on recruiting the right hemisphere and the audiomotor networks as compensatory support. The correlation between proper pSTG activation and improvement in naming suggests that combined singing and neuromodulation protocols (e.g., anodal tDCS over the right pSTG) could be explored to enhance cts further. From a psychosocial perspective, singing groups also provide benefits in mood, self-efficacy, and social participation, which are critical to the functional prognosis of people with aphasia. For research in music and neurotechnology, the work illustrates how designs with new songs, fMRI, and behavioral measures can capture specific changes in learning and plasticity, serving as a model for future interventions in other pathologies (e.g., Parkinson's disease, early dementias).

<p>Rapid Brain Adaptation to Hearing Amplification: A Randomized Crossover Trial of Personal Sound Amplification Products⁽¹²⁾</p>	<p>2025 R a n d o m i z e d crossover trial with EEG</p>	<p>Twenty-five older adults (60–87 years) with and without hearing loss underwent a hearing assessment and a phonological discrimination task in noise under three conditions, in two sessions: without hearing aids and with personal sound amplification products (PSAPs). Listening effort was recorded using self-reports and alpha-band EEG (8–12 Hz), and event-related desynchronization (ERD) was analyzed in left parietotemporal regions.</p>	<p>PSAPs significantly reduced self-reported listening effort. In the hearing unaided condition, alpha ERD weakened as SNR worsened, indicating a failure to sustain the activation necessary to respond to speech in noise. With PSAPs, this decline in ERD was attenuated, with more robust desynchronization in noisy environments (e.g., family gatherings, public spaces). In the musical context, this has implications for the inclusion of older adults in music listening and practice activities: a lower auditory effort load may allow them to enjoy concerts, choirs, or music lessons more, better maintaining the ERD associated with active sound processing. At the level of intervention design, EEG markers can be used to assess whether music-based programs (e.g., rhythmic training, choral singing) plus the use of PSAPs improve not only speech perception but also the ability to process music in noisy environments. This aligns with active-aging strategies, where hearing, communication, and musical participation are considered pillars of quality of life.</p>
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Overall, the reviewed literature suggests that music is not only an aesthetic or recreational stimulus, but also a powerful tool for understanding the functional organization of the brain and for designing effective intervention strategies in language and cognition. The current challenge is to move toward more integrated models that combine neurophysiological evidence, computational approaches, and clinical applications, thereby expanding the therapeutic and educational potential of music in different populations.^(80,81)

Study limitations

Although comprehensive, this review has several limitations that should be considered when interpreting the results. First, there is notable methodological heterogeneity among the included studies: the types of musical interventions, the duration of training, the level of participants' expertise, and the neurotechnological techniques used all vary. This variability makes direct comparisons between studies difficult and limits the ability to establish fully generalizable conclusions.

In addition, many studies have small sample sizes, especially those using fMRI, MEG, or tDCS, which reduces statistical power and increases the risk of false positives or inaccurate estimates. Another significant limitation is the predominance of research conducted in Western contexts, with limited representation of diverse musical cultures, which could influence perceptions, processing, and the cognitive impact of music. Most of the studies reviewed focus on young adults, leaving less evidence on the effects of music training on children, older adults, or populations with specific clinical profiles. Furthermore, the cross-sectional nature of many studies prevents the establishment of firm causal relationships between music and language. Finally, although neurotechnology provides valuable information, challenges remain in standardizing protocols, interpreting neurophysiological signals, and integrating multimodal data. These limitations underscore the need for longitudinal studies with larger samples and cultural diversity, as well as more homogeneous and replicable methodologies.

Practical implications

The findings of this study offer relevant practical implications for education, rehabilitation, and the design of interventions based on music and neurotechnology. In the educational field, evidence shows that incorporating music training programs—especially those focused on rhythm, music reading, and improvisation—can strengthen fundamental language skills, such as verbal fluency, phonological discrimination, and verbal working memory. This suggests that educational institutions could integrate music as a cross-curricular component, not only as an artistic discipline but also as a cognitive tool to optimize language and communication learning.

In the clinical field, results support the use of structured musical interventions in the rehabilitation of patients with post-stroke aphasia, cognitive impairment, neurodevelopmental disorders, or language difficulties. -supported techniques—such as tDCS, EEG, fMRI, or neurofeedback—allow for the monitoring and enhancement of neuroplastic changes that emerge from musical training, favoring more personalized and evidence-based intervention programs. The combination of music and neuromodulation neurotechnology could, for example, improve the functional reorganization of the right hemisphere in patients with damage to classic linguistic networks.

For the design of innovative therapies, the identification of neural networks shared between music and language opens the door to interventions that integrate rhythm, singing, auditory-motor exercises, and real-time brain monitoring technologies. This can translate into more motivating, accessible, and effective treatments. Finally, in the context of healthy aging, continuous musical practice emerges as a strategy for maintaining brain plasticity, preserving executive functions, and delaying age-related cognitive decline.

CONCLUSIONS

The evidence compiled in this review demonstrates that musical training is a powerful tool for enhancing language skills, especially verbal fluency, thanks to its direct influence on auditory, phonological, attentional, and executive processes. The studies reviewed consistently show that music and language share interconnected neural networks that are activated during tasks of auditory discrimination, rhythmic synchronization, phonological articulation, and lexical retrieval. This functional overlap explains the observed transfer effects and positions music training as a practical resource in both healthy and clinical populations.

An integrated analysis of the literature suggests that contemporary neurotechnologies—including EEG, fMRI, MEG, tDCS, and neurofeedback—have enabled a more precise understanding of the mechanisms of music-induced neuroplasticity. These tools have provided robust evidence of functional and structural reorganization in frontotemporal, auditory, and motor networks, offering objective markers for assessing the impact of music training on the brain. Music, therefore, not only modulates neural activity in the short term but also induces lasting changes that strengthen cognitive and linguistic processing.

In the clinical setting, the data support the implementation of musical interventions as a complement to

traditional therapies, especially in post-stroke aphasia, neurodevelopmental disorders, cognitive impairment, and other conditions that affect language. The possibility of combining music with neuromodulation techniques opens up new perspectives for designing personalized rehabilitation programs based on models of brain plasticity and neurophysiological monitoring.

However, there is still a need to expand research toward longitudinal designs, more diverse samples, and greater methodological standardization. Future research should delve deeper into the individual profiles that determine responses to musical interventions and the potential of music to interact with emerging technologies in more precise and adaptive ways.

Overall, this review reaffirms that music training, integrated with neurotechnological tools, represents a promising, accessible, and evidence-based approach to strengthening language and promoting cognitive resilience throughout the life cycle.

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CONFLICT OF INTEREST

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