NeuroMarkers xxx (xxxx) xxx

Contents lists available at ScienceDirect

NeuroMarkers

journal homepage: www.keaipublishing.com/en/journals/neuromarkers/

Review

Understanding Vivaldi's cognitive and neurobiological effects through behavioral and neuroimaging biomarker lenses: A narrative review

Enoch Chi Ngai Lim[a], Chi Eung Danforn Lim[a,b,c,*]

[a] Translational Research Department, Specialist Medical Services Group, Earlwood, NSW, Australia
[b] NICM Health Research Institute, Western Sydney University, Westmead, NSW, Australia
[c] School of Life Sciences, University of Technology Sydney, Ultimo, NSW, Australia

A R T I C L E I N F O

Keywords:
Antonio Vivaldi
Baroque music
Biomarkers
Cognitive enhancement
EEG markers
Functional connectivity
Neural oscillations
Neuroimaging biomarkers
Neurorehabilitation

A B S T R A C T

Research has demonstrated that Antonio Vivaldi's *Four Seasons* concertos boost attention and working memory in young and older populations. Neuroimaging biomarkers derived from electroencephalography, functional magnetic resonance imaging, and other neurophysiological techniques have illustrated that Vivaldi's cheerful "*Spring*" concerto accelerates reaction times, heightens alertness, and stimulates brain activity in regions related to emotion and memory. Quantitative electroencephalography biomarkers reveal enhanced P3a and P3b components during music exposure, indicating improved novelty detection and memory updating processes. Functional connectivity analyses demonstrate that Baroque music stimulates the auditory, motor, and limbic brain circuits due to the repetitive rhythm characteristic of this musical form. Neuroimaging biomarkers of dopaminergic activity show increased activation in reward pathways while listening to Vivaldi's music, which is correlated with improved cognitive performance. In particular, Vivaldi's music has been incorporated into assisted therapy for the elderly to enhance memory, decrease cortisol levels and reduce stress, and aid those with brain injuries in neurorehabilitation, with neuroimaging biomarkers providing objective measures of therapeutic efficacy. Although some studies have conflicting conclusions and benefits that may vary depending on the participants and task context, there is sufficient evidence that Vivaldi's Baroque repertoire is relevant to cognitive psychology and neuroscience. This article aims to give a comprehensive review of the neurobiological mechanisms, neuroimaging biomarkers, and cognitive effects of Vivaldi's music. It presents some contradictory perspectives and research gaps, discussing the future of music therapy and the use of artificial intelligence in interpreting music-brain effects. This review is unique in its focus on the cognitive and neurobiological effects of Baroque music, particularly Vivaldi's *Four Seasons*, a masterpiece that has received very limited dedicated research despite its global recognition.

1. Introduction

Antonio Vivaldi (1678–1741) was a composer of the late Baroque period. He is a talented violinist, best known for his lively concertos, including The *Four Seasons*. His compositions are filled with rhythmic movements, contrasts, and colorful images that inspired contemporaries. Apart from its cultural and historical significance, Vivaldi’s music can provide an attractive subject for scientific discussions on brain-based music theory. Music is a particularly prolific stimulus regarding neuroplasticity: exposure to music engages different brain areas and networks, from auditory cortices to emotional and motor centres.[1–3] Over the past few decades, researchers began to explore how cognition and brain structure are affected by musical exposure.[4] In neuroscience, biomarkers, such as neuroimaging signatures, electrophysiological patterns, and neurochemical indicators, are objective measures that reflect brain structure or function. This review focuses on how such biomarkers have been used to investigate the neural correlates and mechanisms of Vivaldi’s music, thereby bridging cognitive psychology and neurobiological evidence. The idea of “training the brain” through music emerged as a popular trend since the so-called Mozart effect, which hypothesizes that listening to certain types of classical music temporarily increases individuals’ spatial awareness. Although the academic community still debates the interpretation of the Mozart effect, it has become the starting point for

Peer review under the responsibility of Editorial Board of NeuroMarkers.
* Corresponding author at: Translational Research Department, Specialist Medical Services Group, Earlwood, NSW, Australia.
E-mail address: Chi.Lim@westernsydney.edu.au (C.E.D. Lim).

https://doi.org/10.1016/j.neumar.2025.100129
Received 31 May 2025; Received in revised form 10 August 2025; Accepted 9 September 2025
Available online xxxx

Please cite this article as: E.C.N. Lim and C.E.D. Lim, Understanding Vivaldi's cognitive and neurobiological effects through behavioral and neuroimaging biomarker lenses: A narrative review, NeuroMarkers, https://doi.org/10.1016/j.neumar.2025.100129

studying other composers, including Baroque masters such as Vivaldi, and their potential cognitive benefits.

The objective of this narrative review is to synthesize current evidence on the cognitive and neurobiological effects of Vivaldi's music, with an emphasis on identifying, evaluating, and contextualizing neuroimaging and other biomarker findings, while highlighting gaps and future directions for research and therapeutic applications.

2. Search strategy

This narrative review is written for an interdisciplinary audience. It targets researchers, clinicians, and educators in psychology, psychiatry, pediatrics, geriatrics, neuroscience, music therapy, and cognitive rehabilitation. The literature search was completed by the lead author between January 15, 2025 and January 30, 2025. It covered publications from all available years up to December 2024, with no date restrictions.

Four databases were searched: PubMed, PsycINFO, Scopus, and Google Scholar. Search strings combined three elements: composer or genre, cognitive outcomes, and biomarker or measurement terms. Example strings:

- ("Vivaldi" OR "Baroque music") AND (cognition OR "working memory" OR attention OR creativity)
- ("Vivaldi" OR "Baroque music") AND (EEG OR ERP OR "functional connectivity" OR fMRI OR PET OR "neurochemical biomarker*" OR "brain activation")

Filters applied were: English language and human participants. Animal studies were excluded unless providing essential mechanistic context. Reference lists of included papers were also hand-searched.

Inclusion criteria were: empirical human studies reporting behavioral cognitive outcomes or neurobiological biomarkers (electroencephalography (EEG), event-related potential (ERP), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), positron emission tomography (PET), neurochemical, or endocrine markers) during or after exposure to Vivaldi or Baroque music. Exclusion criteria were: non-empirical publications, studies without Baroque music focus, lack of biomarker or cognitive data, inadequate methods reporting, and non-English text.

Finally, a total of 53 references were included in the review analysis.

3. Neurobiological mechanisms of music-induced plasticity

Listening to music triggers numerous neural circuits and causes epigenetic and plastic changes in the brain.[3] For instance, when hearing a Vivaldi concerto, the brain's auditory cortex will first capture the variety of sounds (differentiation of tones, chords, and timber) and deal with the elements of each set.[2,3] Meanwhile, dopamine is released with emotional cues (familiarity, and so forth). This triggers brain structures in the limbic system (such as the amygdala and hippocampus), leading to positive effects on the brain.[1] Vivaldi's music, more often than not, a positive and high-spirited genre of composition, is correlated with higher levels of mood and arousal, resulting in optimal neurochemical conditions for learning, which are approximately elicited by dopamine and noradrenaline. The motor system also engages: rhythmic patterns in Baroque music activate the regions of the basal ganglia and supplementary motor area, both of which partake in timing and movement.[1] Even when the listener is not temporally compensated (increased speed or slowed tempo), the brain's array of timing circuits still "entrains" to the beat, a process in which each oscillatory brainwave locks its phase with the beat of the music. This entrainment can enhance the efficiency of neural processing, effectively "tuning" one's attention networks to the tempo of the music.[5,6]

These widespread activations can result in structural neuroplasticity over repeated exposures: long-term musical training increases volume and connectivity in the auditory, motor, and visuospatial brain regions with grey matter.[4] Passive listening is a milder non-active stimulus than music training, but even listening induces experience-dependent plasticity. Imaging demonstrates that functional connectivity between auditory regions and memory centers can be enhanced for familiar music through repeated co-activation[7] in a manner that potentially has indirect neuroplastic elements. Rewarding and pleasurable music (such as a favorite Vivaldi melody) activates the brain's reward circuitry (ventral striatum) as well, reinforcing the targeted neural pathways of experience.[8] At a molecular level, enjoyable music is tied with the influx of trophic factors and modulators (such as endorphins and possibly brain-derived neurotrophic factor) that sustain synaptic plasticity.[3,9] Listening to music can also enhance neurogenesis indirectly through stress relief and mood elevation in the hippocampus.[3] As illustrated in Fig. 1, music is an enriched sensory experience – a rich and ordered auditory input able to activate parallel neuroplasticity over time.

4. Neuroimaging biomarkers in music-induced cognitive enhancement

Recent advances in neuroimaging techniques have enabled researchers to identify specific biomarkers associated with music-induced cognitive enhancement. fMRI demonstrates that listening to Vivaldi's compositions activates a distributed network including the auditory cortex, prefrontal regions, basal ganglia, and limbic structures, with distinct activation patterns serving as potential biomarkers for music-induced cognitive states.[10] These neuroimaging biomarkers demonstrate increased functional connectivity between frontal and temporal regions during Baroque music exposure, correlating with improved performance on cognitive tasks.[11] The dynamic coupling between these regions, quantifiable through connectivity measures, represents a promising biomarker for predicting individual cognitive responses to musical stimuli.

4.1. Baroque music and brain networks

Published neuroimaging studies[8,11–14] show that Baroque music engages a distributed brain network linking auditory, motor, and limbic systems. fMRI research demonstrates increased functional connectivity between the auditory cortex and prefrontal regions during Baroque listening, which correlates with better performance in attention and working memory tasks.[8,14] Resting-state and task-based connectivity studies indicate that rhythmic structures characteristic of Baroque music enhance coupling within the default mode network and between frontal–temporal circuits, supporting integration of cognitive control and memory processes.[11,14] EEG studies report that Baroque music modulates oscillatory activity, particularly increasing alpha and theta power in frontal and temporal lobes, patterns associated with relaxed alertness and memory encoding.[12] ERP data also suggest that Baroque rhythms facilitate faster novelty detection and memory updating, indicating that network-level synchronization may underlie observed cognitive benefits.[13]

4.2. Musical features and neurobiological markers

Distinct musical features of Baroque compositions, such as tempo and rhythmic regularity, are associated with specific neurobiological responses. Fast tempo in a major mode, common in Vivaldi's works, has been linked to increased frontal beta and parietal alpha power, indicative of heightened alertness and working memory engagement.[12] Regular rhythmic patterns facilitate auditory–motor coupling and predictability, which enhance functional connectivity between auditory cortex, supplementary motor area, and prefrontal regions.[14] ERP studies suggest that predictable rhythmic structures elicit larger P3b components, reflecting improved attentional resource allocation.[13] These findings support the view that discrete musical parameters can selectively modulate neural activity relevant to cognitive performance.

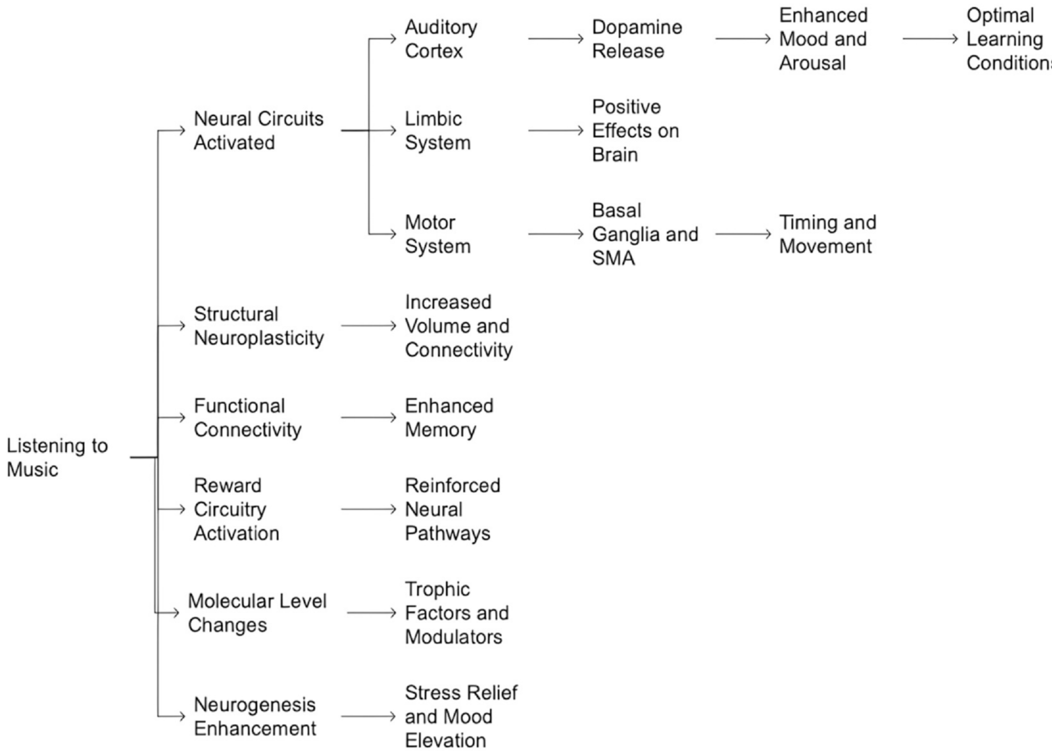

Fig. 1. Neurobiological mechanisms of music induced plasticity.

EEG has provided additional biomarkers of music-induced neural processing. Quantitative EEG examining Baroque music exposure reveal enhanced power in alpha and theta frequency bands, particularly in frontal and temporal regions.[12] These oscillatory changes serve as neurophysiological biomarkers that correlate with improved attention and working memory performance. Riby's EEG investigations specifically demonstrated that Vivaldi's "*Spring*" concerto produced distinct ERP biomarkers, including amplified P3a and P3b components, which index novelty detection and memory updating processes, respectively.[13] These ERP biomarkers provide objective measures of cognitive enhancement that complement behavioral assessments.

Neurochemical biomarkers have further elucidated the mechanisms underlying Vivaldi's cognitive effects. PET has demonstrated increased dopamine release in the ventral striatum during the listening of pleasurable music, with the magnitude of release correlating with subjective enjoyment and subsequent cognitive performance.[14] This dopaminergic response serves as a neurochemical biomarker that may partially explain the arousal-and-mood hypothesis of music-induced cognitive enhancement. Additionally, salivary cortisol measurements provide peripheral biomarkers of stress reduction during exposure to Baroque music, with decreased cortisol levels correlating with improved cognitive function, particularly in memory tasks.[15]

4.3. Cognitive benefits associated with Baroque music

Daily auditory experiences with Vivaldi and other Baroque composers are positively correlated with cognitive functions related to memory, attention, and creative capabilities.[16–18] In a "Vivaldi effect" study, Mammarella et al.[19] presented older adults with a memory task in a control group design after they experienced a short clip of Vivaldi's *Four Seasons*. The results indicated that working memory (digit span and verbal fluency) improved significantly with exposure to the species of classical music in question. This also suggests that listening to a short piece of upbeat Baroque music improves cognition, even in late adulthood. The findings were not caused by passive background noise, as white noise did not improve cognition, indicating that something inherent to the music improved cognition.[19] The authors explained the findings in terms of the arousal-and-mood hypothesis: Vivaldi's dynamic music increased listeners' arousal and mood, as a result, improving performance on the task.[19]

Young adults experience similar benefits. Riby's investigated attention and alertness using Vivaldi's "*Spring*" concerto.[13] While participants listened to the *Spring* and overlaid with different movements of The *Four Seasons*, they took a silence-driven concentration test by detecting visual targets on a screen with brain activity being tracked by EEG. The *Spring* movement is allegro, in a major key, and is most popularly described as "uplifting," associated with a more mentally alert disposition, resulting in swifter reaction times and increased accuracy compared to the silence condition. When *Spring* was playing, participants responded in approximately 394 ms on average, and in silence, 408 ms (with the more subdued "*Autumn*" concerto, a far slower 413 ms). Participants also reported greater effervescence and alertness when listening to the *Spring* music. Reflecting on their behavior, EEG recordings of the participants demonstrated that *Spring* music accelerated the amplitude increase in certain event-based potential in relation to the brain (the P3a component for novelty detection) and memory updating (P3b). To put it another way, Vivaldi's music significantly enhances the Matrix-like signals associated with brain attention and working memory. With these cueing cognitive advantages, piece-specific – *Spring* is the happy haul, and *Autumn* is not – suggesting that it is not "any classical music" but music that plays better with certain characteristics (such as tempo and mood, maybe also familiarity, etc.).

Baroque music could potentially assist in memory forward and retrieval. One study has indicated that older individuals recalled more words on a list when listening to the upbeat Mozart concerto than when listening to silence, and a similar improvement in memory performance was reported with the slow-paced Baroque adagio by Albinoni.[20] Such would indicate that both faster, mood-increasing and slower, relaxing Baroque pieces might assist in memory processes, potentially through different processes (aiding arousal versus reducing stress). Improved memory was noted with both an upbeat major tonality piece and a downbeat minor tonality piece, and both had similar effects on

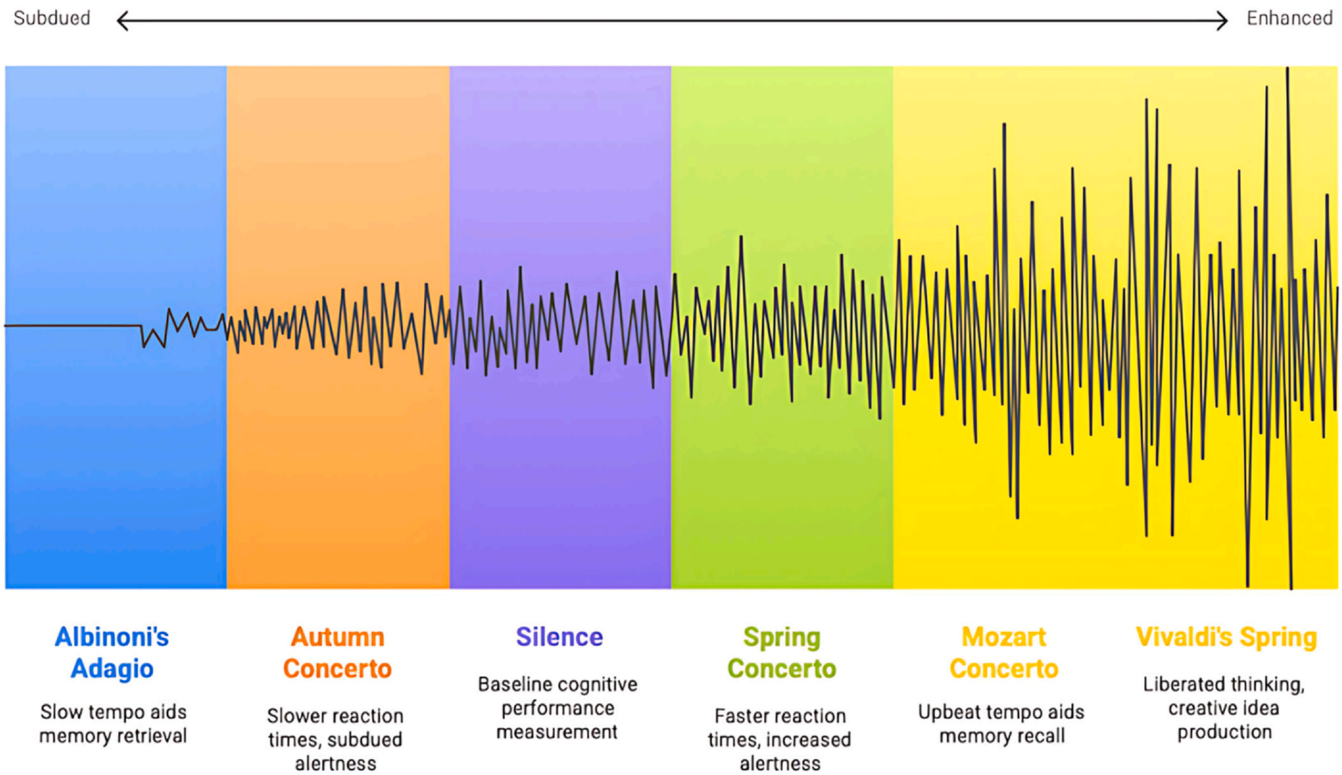

Fig. 2. Baroque music's impact on cognitive function spectrum.

memory, prompting the authors to find that the influence of music is not entirely homogenous and is dependent on the type of task and individual differences.[20]

Ritter and Ferguson[21] investigated the creative thinking abilities of participants with tasks performed under conditions with music and silence. Participants who listened to the upbeat Vivaldi concerto (the first movement of *Spring*) produced more creative uses for common objects through divergent thinking than those who completed tasks in silence. The energetic Baroque compositions appeared to trigger a more liberated and imaginative cognitive state. It demonstrates that music's cognitive benefits extend beyond memory and attention to encompass higher-level mental processes, such as creativity. Music listening offers a simple tool that might be an innovative way to boost creative thinking within educational and workplace environments.[21] Fig. 2 illustrates the structured complexity of Baroque music, which stimulates the brain to create new associations by simultaneously activating multiple networks, leading to enhanced creative idea production.

4.4. Role of tempo and rhythm in cognitive processing

Why would Vivaldi's *Spring* work better than *Autumn*? One reason is the tempo and rhythm of the music. In different movements, Vivaldi creates a driving beat and a strong support for melodic rhythm. Quick tempos tend to elevate physiological arousal: the heart rate and brain frequency can be synchronized with the beats of the music. Within the framework of cognitive tasks, a fast tempo (100–120 bpm, as in *Spring*) can bring the brain to a more alert state, improving the processing speed and reaction readiness.[13] A slow tempo (such as a largo movement at 50–60 bpm, as in some parts of *Autumn*) may relax the listener to the extent of diminishing alertness, slowing down their reaction, and potentially affecting tasks that require a quick response.[13]

Rhythm may also play a critical role. Individuals can recognize beats without physically moving to match the groove due to basal ganglia and complementary motor area activity.[1] Creating a powerful beat or rhythm over a specified duration results in different phases or alignments of neural patterns that achieve signal synchronization to a certain extent.[22] The active process of neural communication influences how signals flow during neural pattern execution because incoming stimuli (new notes and sounds) occur at the optimal oscillation phase.[23] The rhythmic structures in Vivaldi's music can lead to synchronized oscillatory brain activity in attention-related regions with musical rhythms, which helps fine-tune the timing of cognitive processes.

Baroque music is also characterized by its form or framework in terms of its rhythmic regularity and sequences such as arpeggios. For instance, Vivaldi's *Four Seasons* concertos each have a three-part fast–slow–fast form and these structural time changes are often unnoticed by listeners. Directly from the start, the music has a very active introduction. A slower middle part gives room for mental recovery, generating an alternative focus of attention. The quick final movement triggers one's alertness again. The variations in time structure prevent monotony and mental fatigue in the case of prolonged attention. The role is to organize mental stimulation patterns, ensuring that people do not lose attention. This natural variability enhances the ability to maintain attention for an extended period. It also activates the automatic brain responses to musical variations. Such alternations in the patterns align with the natural course of cognition, and the modifications in music are indicative of natural shifts in attention. Some rhythms by Vivaldi might distinctly engage the different neural circuits that process them, for example, the lilting 12/8 m of sections from "*Spring*" that imitate the song of small birds or the martial 4/4 of the finale of many concertos. A constant, rather brisk meter is optimal for cognitive entrainment, as it allows mental activities to align in a continuous cycle.

Examining the emotional rhythm, it is insufficient to say that "*Spring*" evokes a tempo change. In a major key, the composition is a methodical attempt to elicit positive feelings. It depicts the grandeur of nature. The slowness of "*Autumn*" offers a diverse range of movement. Its major key signals the difference, emphasizing the sombre tone. The compositions function differently and generate diverse emotions. Upbeat rhythms are frequently appealing. This increases the variability of thought processes and the extensiveness of attention.[24,25] A slower, sentimental rendition will frequently constrict attention, and lead to

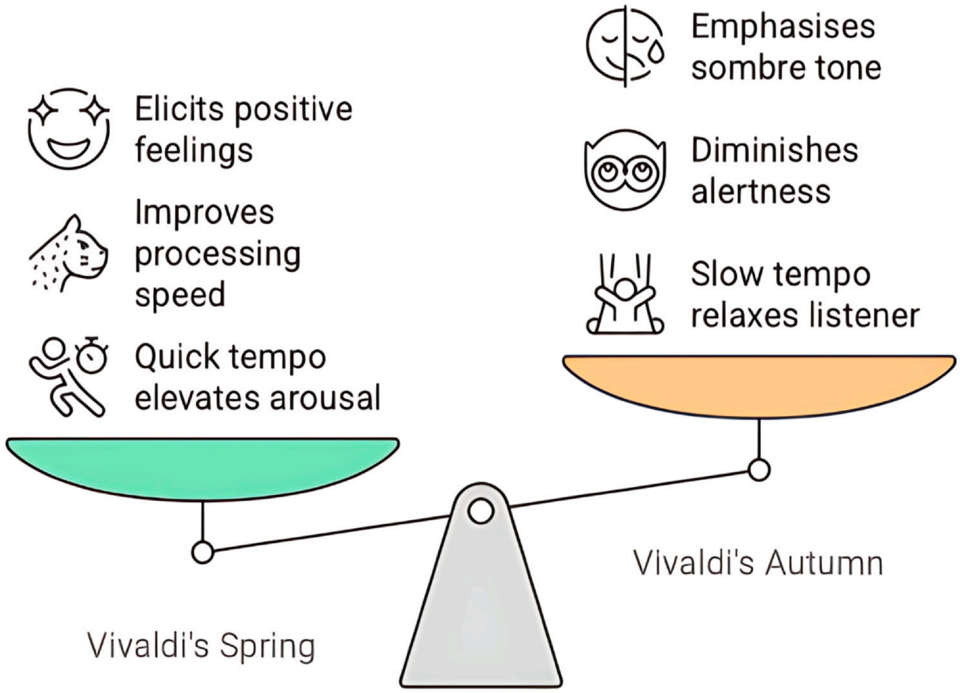

Fig. 3. Comparing tempo and rhythm's cognitive effects.

mind wandering. Despite employing a major key, "*Autumn*" managed to produce no gains in performance.[13] There is a hint that the factors work in conjunction, and a variety enhances brain activity, as illustrated in Fig. 3. The rhythm changes may influence the tempo, and this appears to be a significant level of familiarity with the effect. The separation of these novel aspects of music shows no associative effect, and the results are claimed to synchronize the musician's neural timings with the piece's original timing, leading to improved cognitive effectiveness.

4.5. Therapeutic applications of Vivaldi's music

The interaction of the effect of rejuvenation and the efficiency of cognitive functions attracts the use of Vivaldi's music "therapeutically". Multiple cognitive domains (e.g., attention, memory, motor coordination) are activated by musical interventions to stimulate brain structural and functional changes in restoration.[26] A randomized study with individuals who have experienced traumatic brain injury demonstrated that 3 months of neurological music therapy increased structural connectivity in the brain, as measured by diffusion tensor imaging, with these connectivity changes correlating with improved cognitive outcomes.[26] Despite the intervention involving active music and multiple genres, Vivaldi's violin concertos may serve as a stimulus for motor speed and attentional retraining in injured brains. The dramatic sensory and emotional impact of music may enable the "rewiring" of affected areas, utilizing the brain's plasticity mechanism to introduce new connections.

Patients with Alzheimer's disease and other dementia often benefit from hearing songs that were emotionally significant to them in their past or classical pieces to evoke both positive emotion and perhaps subliminal memories that can serve as reminders of their former identity. Fang et al.[27] suggest that music therapy may be a possible intervention for Alzheimer's disease. Music can be used to activate neural pathways that remain intact in some ways, providing patients with temporary relief from some of their symptoms of cognitive decline. The *Four Seasons* by Vivaldi are compositions that have remained recognizable over the centuries; therefore, they could be considered a good soundtrack for evoking autobiographical memories in patients or to simulate the apathetic patient's response. Mammarella et al.[19] reported that listening to Baroque music causes increased memory probing, even in older but otherwise healthy patients. Health practitioners have started integrating Baroque background music to stimulate patients' cognitive functioning in a comfortable and familiar environment. This strategy is undoubtedly non-invasive, which is an advantage. Anyone can "relatively cheaply and quite safely" play the memory therapy music they like in their homes to improve everyday functioning when they grow older.[20]

Studies have demonstrated that listening to soothing music helps alleviate physiological symptoms of stress, such as lowering cortisol levels and blood pressure,[26] and contributes to increased self-confidence and self-esteem.[27] Although fast pieces by Vivaldi and other Baroque composers stimulate the audience, his slow pieces or the lesser movements in his music call for relaxation. Baroque adagios are commonly included in many playlists for relaxation, and anecdotal evidence suggests that their use increases concentration and helps relieve stress. Music has an indirect benefit on cognitive functioning by reducing anxiety and stress.[28,29] The negative influence of administering chronic stress is known to cause memory and executive function deficits. In a clinical study, surgeons used classical music in the operating room, including Vivaldi's, to calm the patient and reduce the need for anesthesia, and found benefits such as reduced anesthesia use and lower surgery-related cortisol levels.[30]

Rhythmic auditory stimulation neurorehabilitation techniques utilize rhythm to optimize motor and cognitive timing.[31] Rhythmic auditory stimulation is perhaps most known to be used in gait training neuro-rehabilitative strategies in patients with Parkinson's disease[31] (to improve walking rhythm by applying either metronome or music), and it is possible to implement similar strategies in cognitive pacing. In the case of a person with attention deficit hyperactivity disorder or slow processing speed, performing activities with mild Baroque music as background could serve as an external timing cue and increase focus on what is happening.[32,33] Vivaldi's composition could be an organizer for brain activity due to its repetitive rhythm patterns. In addition, therapists observed that music, such as Vivaldi's, could lift the moods of depressed patients and enhance their motivation. Riby[13] proposed that the "*Spring*" concerto, with its evocative imagery and emotional resonance, could be used in therapy to simultaneously improve mood and

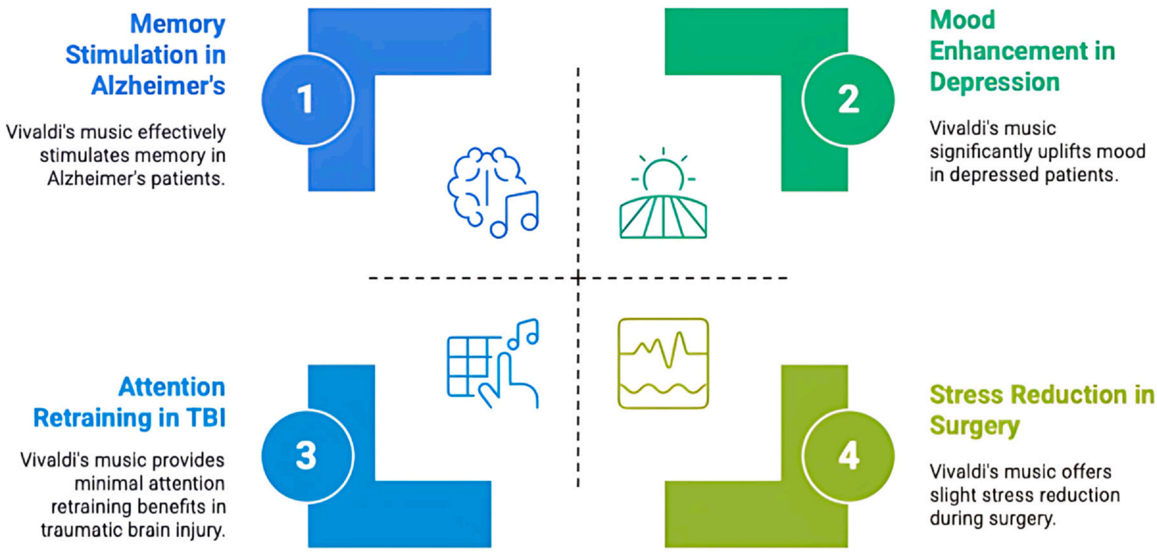

Fig. 4. Therapeutic application of Vivaldi's music. TBI: Traumatic brain injury.

cognitive timing. Fig. 4 summarizes the therapeutic application of Vivaldi's music. There is also a new trend in personalized music prescriptions. For example, if a patient reacts positively to Vivaldi, that could be incorporated into their schedule to adapt their brain to stay focused or calm throughout the day.

5. Limitations

This review has several limitations. The scope is limited by the small number of Vivaldi-specific studies with direct biomarker measurement. Many included studies examine broader categories such as Baroque or classical music, which makes composer-specific effects harder to isolate. Methodological variation across studies is high. Cognitive tasks, biomarker modalities, music exposure lengths, and participant profiles differ, which reduces comparability. Sample sizes in most trials are small and limit statistical power. Publication bias may be present, as positive findings are more likely to be reported than null or negative results. Some conclusions rely on extrapolation from related but non-identical contexts, such as studies using non-Baroque music or mixed-genre interventions.

6. Discussion

6.1. Different schools of thought or controversies

Experts continue to debate whether music truly enhances cognitive abilities despite some evidence suggesting benefits. The Mozart effect stirred both enthusiasm and doubt, as subsequent confirmations produced weaker or null effects.[34] According to the arousal-and-mood hypothesis school of thought, music indirectly leads to cognitive improvement by enhancing mood or arousal levels, which temporarily boosts task performance.[13] The listener's experience of music from Vivaldi (or Mozart) matters more than the actual compositions themselves. Riby's study[13] supports the *Spring*'s advantage due to its "pleasant and arousing" nature, as these elements lead to better cognitive function.

Despite the various beneficial effects of music on cognition, there is the cognitive-capacity hypothesis (distraction hypothesis): this is the idea that background music can draw on cognitive resources and affect task performance, particularly under challenging tasks or among disadvantaged non-distractors.[20] According to this hypothesis (from Kahneman's capacity model of attention), when the task at hand is effortful, one would expect better performance without music, as the latter adds a secondary cognitive load.[20] Some experimental evidence supports this, showing that it is better to be in silence than listening to anything in effortful reading comprehension or memorization tasks. Not all findings on the effects of Vivaldi's music have been positive. Giannouli et al.[35] found that short exposure to Vivaldi's music had no significant effect on young adults' working memory, and they even observed a short-term decrease in verbal working memory after listening to a fast excerpt by Vivaldi. In that study, participants recalled a slightly lower number of digits compared to the silence condition, which supports the distraction hypothesis (the music could have had a high cognitive load or interfered with rehearsal). Interestingly, the same study, though conducted with young adults, found that Vivaldi's music had a positive effect on a different cognitive measure – verbal fluency. While upbeat music may benefit creative or linguistic tasks, it can impair tasks requiring immediate active memorization by causing distraction. These contradictory findings are the subject of an ongoing debate among researchers regarding when the cognitively beneficial effects of music occur versus those that interfere with cognition, as illustrated in Fig. 5.

Individual differences are another confounding factor. Some people are distracted by music,[27,36] while others, by contrast, focus better on it. The potential effect is modulated by several factors, including whether a listener is introverted or extroverted,[36–38] whether they have received musical education, or their personal preference for certain types of music over others. Giannouli et al.[35] demonstrated that higher fluency in words did not result from Mozart's selected music in either young or older adult groups, whereas Vivaldi specifically benefited only the younger audiences. This evidence also suggests that the effects of "classical" music are not uniform, but rather overlap in influences at different ages and tastes of listeners, or, in other words, the composer, style, and age of listeners, or their taste, intersect in more complex ways. In this case, a controversial question is raised: some people claim that the so-called "Mozart/Vivaldi effect" as a concept is oversimplified and that some factors matter, for example, the tempo or consonance of music, and any music could have these aspects that are not present in "normal" popular music. On the other hand, others continue to believe that baroque music may have unique traits (for instance, the 18th-century harmonic style of baroque or very slow +(60 bpm) Largo movements) that are especially helpful for enhancing cognitive capabilities.

While most empirical studies focus on adult participants, limited research has examined cognitive outcomes in children. Carrer[32] reported that background music during time estimation tasks improved temporal processing accuracy in children with attention deficit

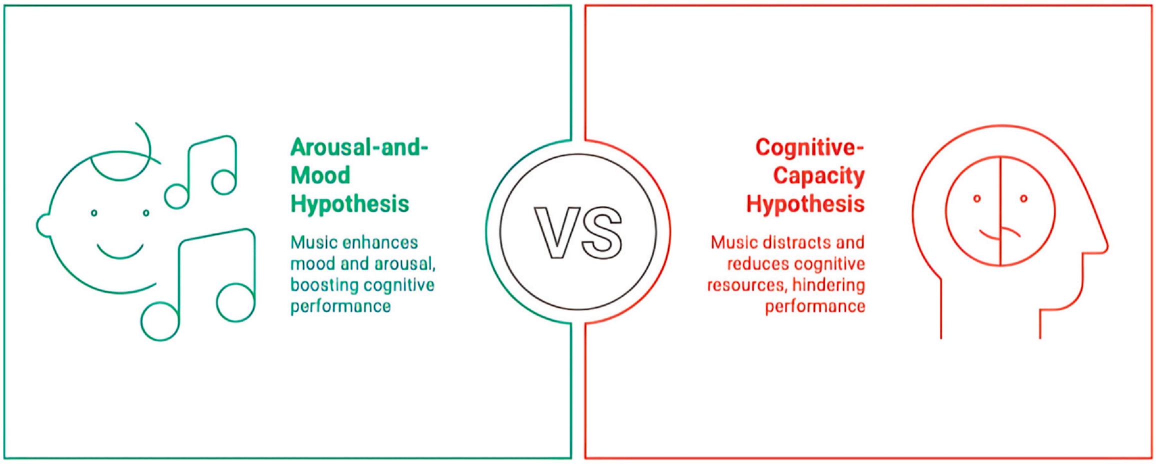

Fig. 5. Which school of thought best explains the impact of music on cognitive performance?

hyperactivity disorder, suggesting benefits in attention-related domains. Piragasam and Unoon[33] observed that background music in preschool learning activities lengthened sustained attention in children with attention deficit hyperactivity disorder. These studies did not use Vivaldi's compositions specifically, and their interventions varied in tempo and style, limiting direct comparison with adult findings. No published studies to date have assessed the effects of Vivaldi's music on verbal fluency or other cognitive measures in healthy children. Summary of included empirical studies on Vivaldi/Baroque music and cognitive or neurobiological outcomes is shown in Table 1**.**

6.2. Individual differences in neurobiological responses

Neurobiological responses to Baroque music vary across individuals. Age-related differences have been observed, with older adults often showing stronger modulation of alpha oscillations during listening, possibly reflecting compensatory attentional mechanisms.[19,20] Participants with cognitive impairment demonstrate altered baseline connectivity patterns, which may influence the degree of network synchronization induced by music.[12] Musical training can enhance auditory–motor integration, resulting in more pronounced frontal–-temporal coupling during rhythmic processing.[14] Emotional state and neurological health also modulate responses, with mood-congruent music producing stronger engagement of reward-related circuitry.[8] These differences highlight the need for stratified analyses in future biomarker research.

6.3. Clinical translation

Clinical translation of music-based interventions is emerging slowly. A pilot trial underway at Memorial Sloan Kettering Cancer Center is testing telehealth music therapy for cognitive impairment in blood cancer survivors (registry ID NCT07052916).[39] This trial aims to assess feasibility and cognitive outcomes in a clinical setting. In Spain, a randomized controlled trial (registered NCT05052034)[40] compared Baroque versus classical music during immediate dental implant surgeries. Both music types significantly reduced anxiety and systolic blood pressure compared to no-music. Another study[41] in stroke patients combined standard cognitive rehabilitation with Baroque music therapy, showing improved cognitive scores (mini-mental state examination), daily functioning (activities of daily living), and reduced depression (Hamilton depression rating scale) versus rehabilitation alone.

Beyond trials, several translational efforts are advancing the field:

- The International Music Therapy Clinical Trial Network (IMTCTnet) coordinates planning and execution of high-quality music therapy trials globally.[42]
- The Institute for Music and Neurologic Function (IMNF) received funding (e.g., from the Parkinson's Foundation) to explore music and light stimulation for dementia via noninvasive digital therapeutics.[43]

No FDA-approved music-based products currently exist. However, music interventions, especially digital platforms like MUSIC & MEMORY®,[44] are widely used in dementia care and supported by healthcare operations. While NIH funding has supported broad music therapy research, composer-specific trials (e.g., investigating Vivaldi or Baroque repertoire) remain rare. There is growing interest in developing patented biometric or artificial intelligence (AI)-guided music delivery systems, though none yet focus on Baroque music. The field is gaining momentum with preliminary clinical trials, institutional support, and therapeutic adoption. Still, wider regulatory guidance, larger trials, and composer-specific protocols are needed for more robust translation.

6.4. Current research gaps and future opportunities

While much interesting research has been reported thus far, several gaps (Fig. 6) still inhibit a complete and nuanced understanding of the effects of Vivaldi's music on cognition and neuroplasticity. The first is methodological consistency and depth, some tend to recruit small sample sizes[35] or focus on testing a particularly narrow aspect of cognition (for instance, a specific type of memory test), making it difficult to generalize the results. On the other hand, a few employed a more extensive scope and pre-registered for replication exist to corroborate such claims as the influence of Vivaldi on increasing the number of words remembered by older adults, but only under certain conditions. In a related vein, however, publication bias is prevalent: that is, a more or less positive effect will get highlighted, while its null or negative outcomes (scenarios where music either had no effect or impaired performance) might go unnoticed. These relative risks are least likely to be published in the "Results" but rather may get thrust into the "Discussion" in an attempt to be blanked as errors and unexplained variances or remain buried as "unpublished data." This may lead to a biased overestimation of the overall benefits of such interventions.

Another missing dimension is in neuroscientific measurement. EEG evidence of acute changes was noted,[13] but what of structural MRI evidence that comes from long-term listening habits? It is challenging to conduct longitudinal research in which one group listens to Baroque music regularly and another does not, and then compare the brain structures. Often, study designs are mainly cross-sectional (e.g., musicians *vs.* non-musicians) or involve intense interventions (such as music therapy in clinical populations). However, the exact neural circuits through which passive listening leads to, for example, memory

Table 1
Summary of included empirical studies on Vivaldi/Baroque music and cognitive or neurobiological outcomes.

Study (Year)	Population	Music intervention	Outcome measures	Biomarker type	Vivaldi-specific?	Key findings
Mammarella et al. (2007)[19]	Healthy older adults	Four Seasons clips	Digit span, verbal fluency	None (behavioural only)	Yes	Upbeat Baroque improved working memory and fluency vs. silence; no effect from white noise
Bottiroli et al. (2014)[20]	Healthy older adults	Upbeat vs. downbeat Baroque	Processing speed, memory	None	No	Upbeat improved processing speed; both tempos improved memory
Ritter and Ferguson (2017)[21]	Adults	Vivaldi Spring	Divergent thinking	None	Yes	Higher creativity scores with upbeat music vs. silence
Riby (2013)[13]	Adults	Spring vs. other movements	Reaction time, accuracy	EEG (P3a, P3b)	Yes	Spring reduced reaction time and increased accuracy; enhanced novelty detection and memory updating
Hofbauer et al. (2024)[24]	Adults	Background music (tempo/valence varied)	Cognitive tasks	None	No	Tempo and valence influenced performance; upbeat improved alertness
Husain et al. (2002)[25]	Adults	Music with varied tempo/mode	Arousal, mood, spatial tasks	None	No	Fast tempo and major mode improved spatial performance; slow tempo reduced alertness
Giannouli et al. (2019)[35]	Adults	Vivaldi excerpts	Working memory, verbal fluency	None	Yes	No WM benefit; verbal fluency improved with upbeat pieces
Gu et al. (2014)[16]	Students	Baroque during learning	Eye-tracking	Eye movement metrics	No	Improved learning efficiency and visual attention
Innes et al. (2018)[15]	Adults with cognitive decline	Meditation or music listening (incl. Baroque)	Biomarkers of ageing, Alzheimer's markers	Blood biomarkers (amyloid-β, telomerase)	No	Reduced amyloid-β; increased telomerase activity
Liu et al. (2020)[11]	Adults with depression	Music perception (incl. Baroque)	EEG connectivity	EEG functional connectivity	No	Enhanced connectivity in emotion-related networks
Xu et al. (2024)[12]	Cognitive impairment patients	Music therapy (incl. Baroque)	EEG power spectra	EEG (alpha/theta)	No	Increased alpha/theta in frontal and temporal areas
Saari et al. (2018)[14]	Adults	Musical training	Brain feature decoding	fMRI	No	Enhanced dynamic brain processing with music expertise
Menon and Levitin (2005)[8]	Adults	Pleasurable music listening	Brain activation	fMRI	No	Activation of mesolimbic reward circuitry
Angelucci et al. (2007)[9]	Mice	Music exposure	BDNF levels	BDNF assay	No	Increased BDNF with enjoyable music
Emami et al. (2023)[26]	Dementia care dyads	Care music intervention	Salivary cortisol	Salivary cortisol	No	Reduced cortisol with music sessions
Irish et al. (2006)[28]	Mild Alzheimer's	Music listening	Memory recall	None	No	Improved recall with familiar classical pieces
Koelsch et al. (2011)[30]	Surgery patients	Music listening (incl. Baroque)	Cortisol, anaesthetic use	Salivary cortisol, anaesthetic dose	No	Lower cortisol and reduced propofol requirement
Paolantonio et al. (2020)[27]	Nursing home residents	Group music-making	Wellbeing scales	None	No	Improved self-reported wellbeing
Burns et al. (2002)[29]	Adults	Music listening	Stress measures	Physiological stress markers	No	Lower perceived stress and physiological stress
Thaut et al. (1996)[31]	Parkinson's patients	Rhythmic auditory stimulation	Gait metrics	None	No	Improved walking rhythm and speed
Carrer (2015)[32]	Children with ADHD	Background music during tasks	Time processing accuracy	None	No	Improved time estimation and focus during tasks, suggesting benefit to attention timing
Piragasam and Unoon (2018)[33]	Preschool children with ADHD	Background music during learning	Sustained attention duration	None	No	Increased sustained attention during structured learning activities

"Vivaldi-specific?" column: Yes if Vivaldi's compositions were the main music stimulus; No if only broader Baroque/classical music was tested. "Biomarker type" column specifies the neuroscience or physiological measure used. "None" indicates purely behavioral outcomes. ADHD: Attention deficit hyperactivity disorder; ADL: Activities of daily living; BDNF: brain-derived neurotrophic factor; DTI: diffusion tensor imaging; EEG: electroencephalography; ERP: event-related potential; fMRI: functional magnetic resonance imaging; HAMD: Hamilton depression rating scale; MMSE: mini-mental state examination; PET: positron emission tomography; WM: working memory.

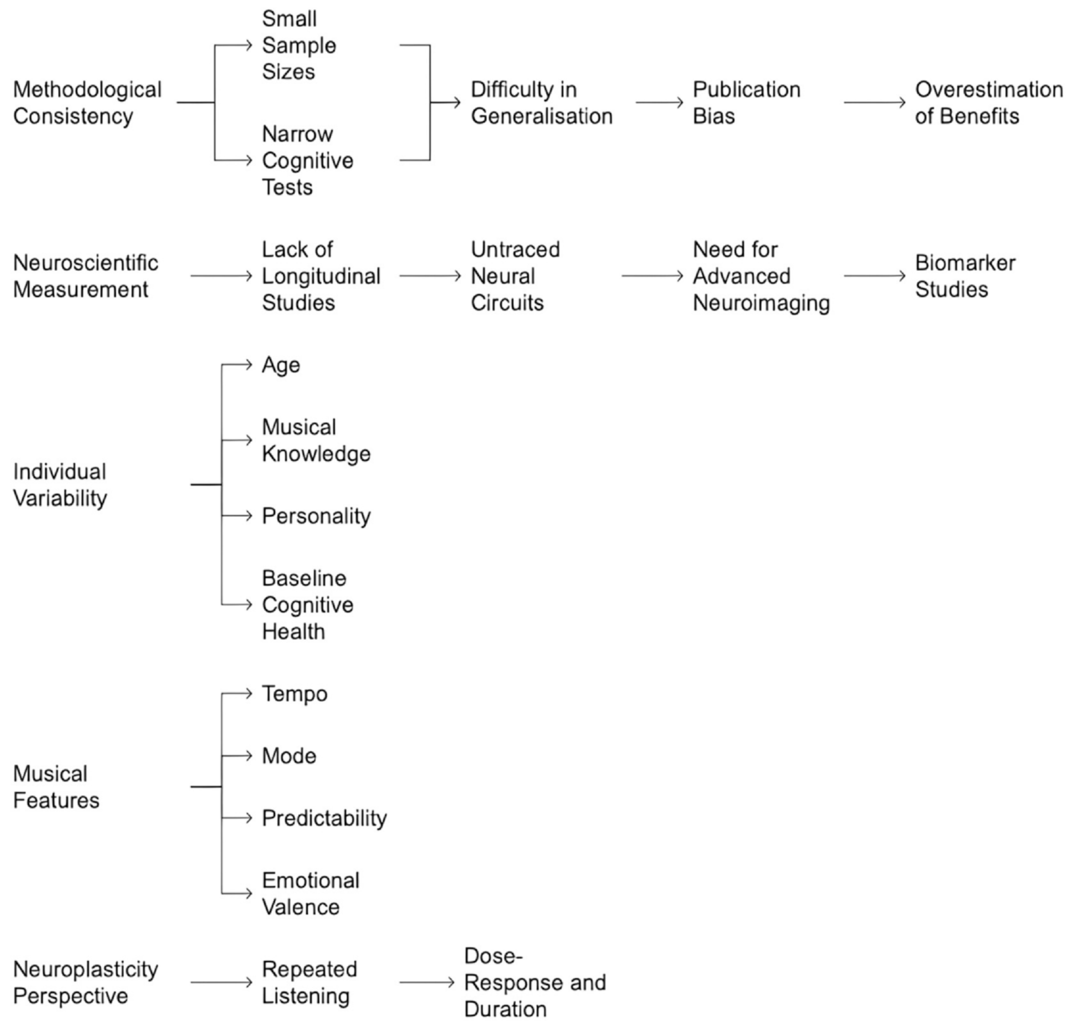

Fig. 6. Research gaps and future opportunities in music and cognition.

consolidation are still rather untraced. Are hippocampal activity patterns involved in such music-listening learning sessions different? Is functional connectivity between frontal and temporal lobes higher when background Baroque music plays during a task? Such questions could be answered using advanced neuroimaging (e.g. fMRI, MEG). There is also a need for more research that utilizes biomarkers, measuring neurochemicals or neurotrophic factors, both before and after music exposure, to determine whether music, through its biochemical milieu, reliably triggers plasticity.

The development of standardized neuroimaging biomarkers represents a critical frontier in music cognition research. While preliminary research has identified potential biomarkers, methodological inconsistencies limit their clinical utility and research applicability. Future investigations should focus on establishing reliable neuroimaging biomarkers that can predict individual responses to music interventions and objectively measure their cognitive effects.[45] Multimodal approaches combining EEG, fMRI, and other neurophysiological measures could yield composite biomarkers with greater sensitivity and specificity than single-modality assessments. Machine learning algorithms applied to these multimodal datasets could identify patterns of neural activity that serve as robust biomarkers for music-induced cognitive enhancement.[46]

Longitudinal research employing repeated neuroimaging assessments are needed to establish the temporal dynamics of biomarker changes. Such investigations could determine whether acute biomarker responses to Vivaldi's music predict long-term cognitive benefits and neuroplastic changes. Additionally, research should explore whether these neuroimaging biomarkers differ across demographic groups, including age, musical training, and cognitive status. The identification of biomarker profiles associated with optimal responses to music interventions could facilitate personalized approaches to music therapy and cognitive enhancement.[47]

The role of individual variability in music is under-researched. The impact of Vivaldi's music should be systematically studied in terms of such personal factors as age, musical knowledge, personality, and baseline cognitive health. Giannouli's study[35] made a good start at comparing younger and older adults, concluding that some differences existed. More such stratified analyses could identify subgroups for whom Baroque music is most beneficial. It might turn out that older adults benefit more than young (or *vice versa*) or that novices benefit differently than those with musical training (for instance, musicians might find simple music under-stimulating).

It is still unclear which musical features are the most important. Is it the sense of tempo, the mode (major or minor), the predictability, or the emotional valence? Most researchers seem to want to select one piece of music vs. another for study purposes, but few deconstruct the music itself. With modern music information retrieval techniques, certain features of Vivaldi's compositions (e.g. note density, melodic complexity, rhythmic regularity) could be quantified and correlated with cognitive outcomes. That would help to look beyond the composers and better understand the active ingredients in the music.

From a neuroplasticity perspective, very little is known about how repeated listening (compared to a single session) could lead to change in the brain. Most cognition tests are repeated (expressed as a response

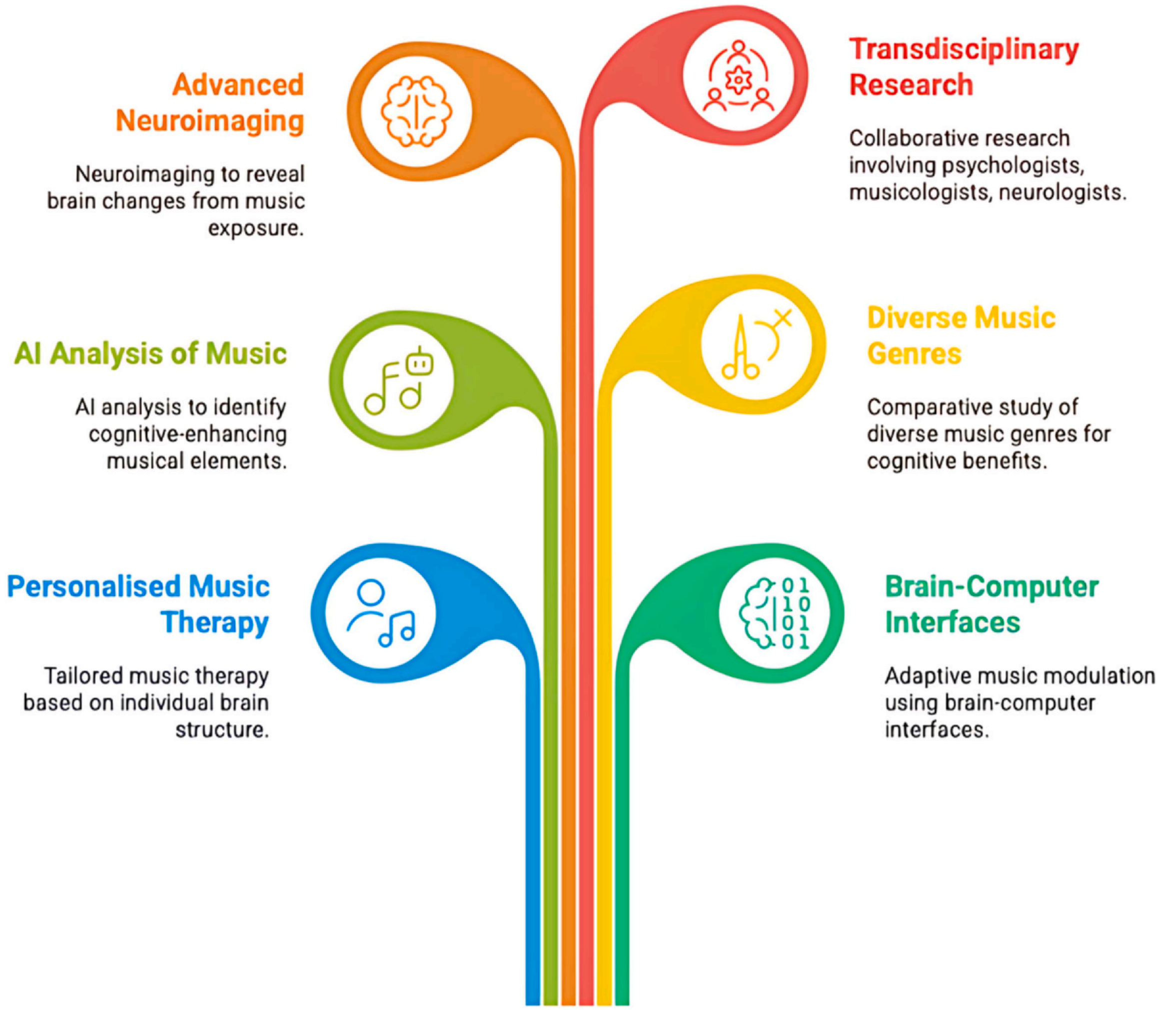

Fig. 7. Future of music and cognition. AI: Artificial intelligence.

speed *vs.* time measure) across minutes to hours. For the results to be generalized to real-world interventions, it is vital to understand the dose-response and duration of effects.

6.5. Potential future developments

Extra dimensions in this matter can be discovered through evolving research and technological trends. One such direction appears to be utilizing personalized music therapy according to one's brain and cognitive structure. Such potentials may include diagnostics regarding the most influential factors on a particular person's attention or memory characteristics, as well as the possibility for an expert to "prescribe" such daily listening, for example, Vivaldi or another composer. Individualization of music therapy could lead to specific results due to variability exposed by some studies.[48,49] Such a trend correlates with another, brain-computer interfaces and adaptive algorithms.[50,51] Musical modulation based on EEG is already being utilized in science, for example, with the theta/beta ratio in situational algorithms. If attention drops, the system can trigger a more stimulating wave or increase the volume to try to attract attention with more aggression. An interactive Vivaldi designed for a heart-brain connection that is tailored to a particular user could potentially address the issue of music being too dull or too distracting, as it learns to adapt in real-time based on current data, thereby ensuring constant stimulation and maintaining cognitive performance.

The integration of real-time neuroimaging biomarkers with music delivery systems represents an exciting frontier in personalized cognitive enhancement. Closed-loop systems that monitor neural biomarkers during music exposure could dynamically adjust musical parameters to optimize cognitive effects.[52] For instance, if EEG biomarkers indicate declining attention, the system could transition to more stimulating segments of Vivaldi's compositions. Similarly, if neuroimaging biomarkers suggest excessive arousal, the system could introduce calming musical elements to restore optimal cognitive functioning. Such biomarker-guided music interventions could maximize cognitive benefits while minimizing individual variability in responses.

Advances in portable neuroimaging technologies, including wearable EEG and fNIRS, are making biomarker monitoring increasingly accessible outside laboratory settings.[48] These technologies could enable continuous assessment of neuroimaging biomarkers during daily activities, providing insights into how Vivaldi's music influences cognition in naturalistic environments. The development of validated biomarker signatures for specific cognitive states could transform music from a passive listening experience into a precision tool for cognitive enhancement and therapeutic intervention.

Additional parallel research that helps determine how various elements of Baroque music improve cognition includes AI analysis of music and big data from cognitive tests.[53] Such an analysis might find, for example, that some specific chord progressions or rhythmic patterns might universally stimulate positive arousal in most people, or that a mix of moderate tempo and major mode is a maximally beneficial combination for memory retention in 70 % of people, and so forth. Future composers (or perhaps even music composition systems supported by AI) might compose so-called "neurostimulation sonatas" with audial elements inspired by Baroque styles in order to target brain rhythms and plasticity in very specific manners.

Expanding the study of non-Western and culturally diverse genres of music for comparison is another interesting possibility. For example, Baroque music might not be uniquely breathtaking; perhaps the same cognitive benefits can be found in Chinese or Indian classical ragas or energetic upbeat pop music. Whether Vivaldi's music is fundamentally unique or an example of a more significant trend may be determined if diverse music is studied. If it is the former, certain techniques could be borrowed, such as rhythmic entrainment, from other genres. If there is anything unique about the Baroque structure, the feature that helps inform the selection of music and neural theories regarding the processing of patterns should be used.

Subtle changes to the brain may become apparent through advanced neuroimaging techniques. High-resolution functional MRI, diffusion tensor imaging, and connectivity analyses may reveal novel insights, allowing future research to determine whether listening to Baroque music influences white matter or enhances network coupling. The latter effect may be explicitly observed in default mode and executive networks after listening for a month. Animal model research and optogenetics could allow for examining the direct influence of sound patterns on neural circuits despite the mechanisms of such stimulation differing significantly from those that human beings experience during a Vivaldi concert. Fig. 7 showcases the future direction of the association between music and cognition.

7. Conclusion

Future transdisciplinary research in music and neurocognition requires input from consumers, psychologists, musicians, and neurologists. As the world's population ages, the demand for non-pharmacological interventions to support the maintenance of cognition increases. Music could be a good candidate, it is accessible and pleasant, and Vivaldi's immortal works could become the flagships of future cognitive wellness programs.

CRediT authorship contribution statement

Enoch Chi Ngai Lim: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chi Eung Danforn Lim:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Investigation, Formal analysis, Conceptualization.

Funding

None.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

Figs. 1–7 in this manuscript were generated using Napkin AI (V3, 2024; beta version) based on textual descriptions written entirely by the authors. Napkin AI was used solely for visual representation and did not contribute to the conceptual development, scientific content, or writing of the manuscript. All outputs generated by the AI tool were thoroughly reviewed and approved by the authors.

Acknowledgements

Not applicable.

References

1. Toader C, Tataru CP, Florian IA, et al. Cognitive crescendo: how music shapes the brain's structure and function. *Brain Sci.* 2023;13(10):1390. https://doi.org/10.3390/brainsci13101390
2. Perrone-Capano C, Volpicelli F, di Porzio U. Biological bases of human musicality. *Rev Neurosci.* 2017;28(3):235–245. https://doi.org/10.1515/revneuro-2016-0046
3. Reybrouck M, Vuust P, Brattico E. Music and brain plasticity: how sounds trigger neurogenerative adaptations. In: Kolb B, ed. *Neuroplasticity: Insights of Neural Reorganization.* Rijeka, Croatia: InTech; 2018:85–102. https://doi.org/10.5772/intechopen.74318
4. Rodrigues AC, Loureiro MA, Caramelli P. Musical training, neuroplasticity and cognition. *Dement Neuropsychol.* 2010;4(4):277–286. https://doi.org/10.1590/S1980-57642010DN40400005
5. Doelling KB, Poeppel D. Cortical entrainment to music and its modulation by expertise. *Proc Natl Acad Sci U S A.* 2015;112(45):E6233–6242. https://doi.org/10.1073/pnas.1508431112
6. Damsma A, de Roo M, Doelling KB, Bazin PL, Bouwer FL. Tempo-dependent selective enhancement of neural responses at the beat frequency can be explained by both an oscillator and an evoked model. *bioRxiv.* 2024. https://doi.org/10.1101/2024.07.11.603023
7. Zatorre RJ, Salimpoor VN. From perception to pleasure: music and its neural substrates. *Proc Natl Acad Sci U S A.* 2013;110(2):10430–10437. https://doi.org/10.1073/pnas.1301228110
8. Menon V, Levitin DJ. The rewards of music listening: response and physiological connectivity of the mesolimbic system. *Neuroimage.* 2005;28(1):175–184. https://doi.org/10.1016/j.neuroimage.2005.05.053
9. Angelucci F, Marco F, Ricci E, Padua L, Sabino A, Tonali PA. Investigating the neurobiology of music: brain-derived neurotrophic factor modulation in the hippocampus of young adult mice. *Behav Pharm.* 2007;18(5-6):491–496. https://doi.org/10.1097/FBP.0b013e3282d28f50
10. Curzel F, Brigadoi S, Cutini S, Ferreri L. Lights on music cognition: a systematic and critical review of fNIRS studies. *Brain Cogn.* 2024;176:106200. https://doi.org/10.1016/j.bandc.2024.105980
11. Liu W, Wang X, Xu J, et al. Functional connectivity of major depression disorder using ongoing EEG during music perception. *Clin Neurophysiol.* 2020;131(10):2345–2354. https://doi.org/10.1016/j.clinph.2020.06.014
12. Xu M, Zhu Y, Xu X, Zheng W. EEG biomarkers analysis in different cognitive impairment levels based on music therapy. *Front Neurol.* 2024;15:1358167. https://doi.org/10.3389/fneur.2024.1358167
13. Riby LM. The joys of spring: changes in mental alertness and brain function. *Exp Psychol.* 2013;60(2):71–79. https://doi.org/10.1027/1618-3169/a000166
14. Saari P, Burunat I, Brattico E, Toiviainen P. Decoding musical training from dynamic processing of musical features in the brain. *Sci Rep.* 2018;8(1):708. https://doi.org/10.1038/s41598-018-19177-5
15. Innes KE, Selfe TK, Khalsa DS, Kandati S. Effects of meditation and music-listening on blood biomarkers of cellular aging and Alzheimer's disease in adults with subjective cognitive decline: an exploratory randomized clinical trial. *J Alzheimers Dis.* 2018;66(3):947–970. https://doi.org/10.3233/JAD-180164
16. Gu R, Zhang J, Zhou J, Tong MS. *The Baroque music's influence on learning efficiency based on the research of eye movement. Proceedings of the 2014 IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE)*. 2014; 2014:511–515. https://doi.org/10.1109/TALE.2014.7062619 IEEE.
17. Schneider C, Hunter EG, Bardach SH. Potential cognitive benefits from playing music among cognitively intact older adults: a scoping review. *J Appl Gerontol.* 2019;38(12):1763–1783. https://doi.org/10.1177/0733464817751198
18. Honing H, Ploeger A. Cognition and the evolution of music: pitfalls and prospects. *Top Cogn Sci.* 2012;4(4):513–524. https://doi.org/10.1111/j.1756-8765.2012.01210.x
19. Mammarella N, Fairfield B, Cornoldi C. Does music enhance cognitive performance in healthy older adults? The vivaldi effect. *Aging Clin Exp Res.* 2007;19(5):394–399. https://doi.org/10.1007/BF03324720
20. Bottiroli S, Rosi A, Russo R, Vecchi T, Cavallini E. The cognitive effects of listening to background music on older adults: processing speed improves with upbeat music, while memory seems to benefit from both upbeat and downbeat music. *Front Aging Neurosci.* 2014;6:284. https://doi.org/10.3389/fnagi.2014.00284
21. Ritter SM, Ferguson S. Happy creativity: listening to happy music facilitates divergent thinking. *PLoS One.* 2017;12(9):e0182210. https://doi.org/10.1371/journal.pone.0182210
22. Tierney A, Kraus N. Neural responses to sounds presented on and off the beat of ecologically valid music. *Front Syst Neurosci.* 2013;7:14. https://doi.org/10.3389/fnsys.2013.00014
23. Merchant H, Grahn J, Trainor L, Rohrmeier M, Fitch WT. Finding the beat: a neural perspective across humans and non-human primates. *Philos Trans R Soc Lond B Biol Sci.* 2015;370(1664):20140093. https://doi.org/10.1098/rstb.2014.0093
24. Hofbauer LM, Lachmann T, Rodriguez FS. Background music varying in tempo and emotional valence differentially affects cognitive task performance: experimental within-participant comparison. *J Cult Cogn Sci.* 2024;8(1):139–150. https://doi.org/10.1007/s41809-024-00144-8
25. Husain G, Thompson WF, Schellenberg EG. Effects of musical tempo and mode on arousal, mood, and spatial abilities. *Music Percept.* 2002;20(2):151–171. https://doi.org/10.1525/mp.2002.20.2.151

26. Emami A, Theorell T, Kim H, et al. Assessing stress using repeated saliva concentration of steroid hormones in dementia care dyads: results from a controlled pilot care music intervention. *Ups J Med Sci.* 2023;128:9340. https://doi.org/10.48101/ujms.v128.9340
27. Paolantonio P, Cavalli S, Biasutti M, Pedrazzani C, Williamon A. Art for ages: the effects of group music making on the wellbeing of nursing home residents. *Front Psychol.* 2020;11:575161. https://doi.org/10.3389/fpsyg.2020.575161
28. Irish M, Cunningham C, Walsh JB, et al. Investigating the enhancing effect of music on autobiographical memory in mild Alzheimer's disease. *Dement Geriatr Cogn Disord.* 2006;22(2):108–120. https://doi.org/10.1159/000093487
29. Burns JL, Labbé É, Arke B, et al. The effects of different types of music on perceived and physiological measures of stress. *J Music Ther.* 2002;39(2):101–116. https://doi.org/10.1093/jmt/39.2.101
30. Koelsch S, Fuermetz J, Sack U, et al. Effects of music listening on cortisol levels and propofol consumption during spinal anesthesia. *Front Psychol.* 2011;2:58. https://doi.org/10.3389/fpsyg.2011.00058
31. Thaut MH, McIntosh GC, Rice RR, Miller RA, Rathbun J, Brault J. Rhythmic auditory stimulation in gait training for parkinson's disease patients. *Mov Disord.* 1996;11(2):193–200. https://doi.org/10.1002/mds.870110213
32. Carrer LRJ. Music and sound in time processing of children with ADHD. *Front Psychiatry.* 2015;6:127. https://doi.org/10.3389/fpsyt.2015.00127
33. Piragasam GA, Unoon ARI. Attention span remediation of attention deficit hyperactive disorders (ADHD) preschoolers with music as learning background. *Int J Acad Res Prog Educ Dev.* 2018;7(4):148–157. https://doi.org/10.6007/ijarped/v7-i4/4843
34. Schellenberg EG. Music and cognitive abilities. *Curr Dir Psychol Sci.* 2005;14(6):317–320. https://doi.org/10.1111/j.0963-7214.2005.00389.x
35. Giannouli V, Kolev V, Yordanova J. Is there a specific Vivaldi effect on verbal memory functions? Evidence from listening to music in younger and older adults. *Psychol Music.* 2019;47(3):325–341. https://doi.org/10.1177/0305735618757901
36. Cassidy G, MacDonald R. The effect of background music and background noise on the task performance of introverts and extraverts. *Psychol Music.* 2007;35(3):517–544. https://doi.org/10.1177/0305735607076444
37. Avila C, Furnham A, McClelland A. The influence of distracting familiar vocal music on cognitive performance of introverts and extraverts. *Psychol Music.* 2012;40(1):84–93. https://doi.org/10.1177/0305735611422672
38. Furnham A, Allass K. The influence of musical distraction of varying complexity on the cognitive performance of extroverts and introverts. *Eur J Pers.* 1999;13(1):27–38. https://doi.org/10.1002/(SICI)1099-0984(199901/02)13:1 < 27::AID-PER318 > 3.0.CO;2-R
39. Memorial Sloan Kettering Cancer Center. Telehealth music therapy for cognitive impairment in survivors of hematopoietic stem cell transplant. ClinicalTrials.gov identifier: NCT07052916. Updated August 10, 2027. Accessed August 10, 2028. ⟨https://clinicaltrials.gov/study/NCT07052916⟩.
40. Pellicer LE, Rubio JLM, Casañas E, et al. Immediate implant placement influenced by musical flow: a prospective randomized controlled clinical trial. *BMC Oral Health.* 2024;24(1):628. https://doi.org/10.1186/s12903-024-04366-8
41. Guan Wi, Wang GH, MiaO FR. Effect of baroque music therapy on cognitive impairment after stroke. *Chin J Alzheimers Dis Relat Disord.* 2022;5(4):304–307. https://doi.org/10.3969/j.issn.2096-5516.2022.04.0
42. University of Melbourne. International Music Therapy Clinical Trial Network (IMTCTnet). Creative Arts and Music Therapy Research Unit. University of Melbourne Faculty of Fine Arts and Music Website. Accessed August 10, 2025. ⟨https://finearts-music.unimelb.edu.au/research/creative-arts-music-therapy-research-unit/international-music-therapy-clinical-trial-network⟩.
43. Institute for Music and Neurologic Function. Institute for Music and Neurologic Function. Updated August 10, 2025. Accessed August 10, 2026. ⟨https://www.imnf.org⟩.
44. Music & Memory [Internet]. Updated August 10, 2024. Accessed August 10, 2025. ⟨https://musicandmemory.org/resources/⟩.
45. Chen J, Huang Y, Yang S, Wang G, Liu D. Editorial: neuroimaging biomarkers and cognition in alzheimer's disease spectrum. *Front Aging Neurosci.* 2022;14:848719. https://doi.org/10.3389/fnagi.2022.848719
46. Faber S, Kaya EM, McAdams S. Multimodal dynamic network activity during naturalistic music listening. *Imaging Neurosci.* 2025;1(1):100–115. https://doi.org/10.1162/imag_a_00413
47. Andrews E, Eierud C, Banks D, et al. Effects of lifelong musicianship on White matter integrity and cognitive brain reserve. *Brain Sci.* 2021;11(1):67. https://doi.org/10.3390/brainsci11010067
48. Lai-Tan N, Philiastides MG, Kawsar F, Deligianni F. Toward personalized music therapy: a neurocomputational modeling perspective. *IEEE Pervasive Comput.* 2023;22:27–37. https://doi.org/10.1109/MPRV.2023.3285087
49. Lai N.Y., Philiastides M.G., Kawsar F., Deligianni F. Towards personalised music therapy: a neurocomputational modelling perspective. arXiv. 2023. doi: 10.48550/arXiv.2305.14364.
50. Miranda ER. Brain-computer music interface for composition and performance. *Int J Disabil Hum Dev.* 2006;5(2):119–126. https://doi.org/10.1515/IJDHD.2006.5.2.119
51. Miranda ER. Plymouth brain-computer music interfacing project: from EEG audio mixers to composition informed by cognitive neuroscience. *Int J Arts Technol.* 2010;3(2-3):154–176. https://doi.org/10.1504/IJART.2010.032562
52. Yuan Y, Zhao Y. The role of quantitative EEG biomarkers in Alzheimer's disease: current status and future directions. *Front Aging Neurosci.* 2025;17:1522552. https://doi.org/10.3389/fnagi.2025.1522552
53. Lupker JA, Turkel WJ. Music theory, the missing link between music-related big data and artificial intelligence. *Digit Humanit Q.* 2021;15(1):520⟨http://www.digitalhumanities.org/dhq/vol15/100520/000520.html⟩.