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MUSIC-BASED AUDITORY STIMULATION AND ITS EFFECTS ON GENE EXPRESSION RELATED TO NEURAL FUNCTION

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Abstract

Music stimulation of the auditory system has become a key interdisciplinary field of research involving neuroscience, molecular biology, psychology and cognitive science. Recent studies indicate that music is not only a cultural and emotional experience, but also a biological stimulus which can regulate neural activity, synaptic plasticity, and gene expression involved in brain function. This paper provides an overview of the connection between auditory stimuli (music) and its impact on neural plasticity genes, neurotransmission genes, memory genes and emotional regulation genes. Human and animal studies have shown that music exposure can affect the expression of immediate early genes (IEGs) like FOS, ARC and ZENK, and of neurotrophic factors like Brain-Derived Neurotrophic Factor (BDNF). These molecular changes lead to increased neural connectivity, better cognitive function, reduced stress and neuroprotection. Listening and musical training have been demonstrated to modify the transcriptomic pathway related to dopamine signaling, synaptic transmission and cortical plasticity. Further, CREB mediated signaling of prenatal and early developmental auditory stimulation to the hippocampus and to memory related pathways. Music is also shown to involve large-scale neural networks in functional imaging studies, including those of the auditory cortex, limbic system, hippocampus, and prefrontal cortex. This paper summarizes the available literature on music-induced neuroplasticity at the molecular level and examines the potential of music in therapeutic interventions for neurological and psychiatric diseases. The results suggest that music is a biologically impactful tool that can affect neural regulation of genes and functional brain adaption. In the future, combining genomics, neuroimaging, and auditory neuroscience could further elucidate the therapeutic potential of music-based interventions in improving cognitive health and neural recovery.

Keywords: *Music therapy, auditory stimulation, gene expression, neuroplasticity, neural function.*

1. Introduction

Music has played an important role in human civilization for thousands of years and has been found to affect the way people express emotion, communicate culture, remember things and interact with others[1]. Today, music is becoming a more and more influential auditory signal that can induce measurable physiological and neurological changes in the human brain[2]. In addition to the emotional and psychological effects, more recent scientific studies have shown that music can provoke molecular and genetic responses related to neural plasticity, cognitive processing and brain development[3]. The interplay between music perception and gene expression thus has emerged as a new interdisciplinary research field with a focus on neuroscience, molecular biology, psychology and auditory science[4].

Music stimulates the auditory cortex, the limbic system, the hippocampus, the cerebellum and the prefrontal cortex; therefore music activates complex neural pathways[5]. These brain areas are linked to memory, emotion, attention, and motor coordination. Functional neuroimaging studies have demonstrated that listening to music activates both cortical and subcortical regions at the same time, resulting in coordinated activity across distributed networks of the brain[6]. Temporary electrophysiological changes are not the only effects of music-induced neural activation; music can also have long-lasting effects on molecular adaptations, for example by regulating specific genes that relate to the mechanisms of synaptic plasticity and neuronal survival[7].

Gene expression means the process whereby information in the gene, coded in the DNA, is transformed into functional molecules like proteins[8]. The neuronal activity can lead to changes in the transcription mechanisms of the neurons via the activation of signaling pathways, resulting in changes to the strength of synapses and the connectivity of neurons[9]. The increasing evidence of the ability of listening to music to induce transcriptional responses in the brain as an environmental stimulus is growing[10]. Human studies and studies with songbirds and rodents have shown that exposure to music and sound can trigger genes that are known to be involved in activity-dependent processes like neural plasticity and memory consolidation (FOS, ARC, ZENK, DUSP1)[11].

The molecule that has been most studied in relation to music-induced neural plasticity is Brain-Derived Neurotrophic Factor (BDNF). Neurotrophin BDNF is crucial for neuronal growth, synaptic plasticity, and learning processes. Up-regulation of BDNF has been linked to improved cognitive function and neuroprotection. Studies show that listening to music can stimulate the brain and boost the presence of BDNF in the blood and activate CREB-dependent pathways that are related to memory and hippocampal development[12]. These results suggest music has a direct effect on molecular systems that are directly tied to learning and neural adaptation.

Studies on musicians offer additional proof of the linkage between music and gene regulation[13]. Changes in brain structure and function have been observed in professional musicians relative to control (non-musicians) groups, with greater cortical connectivity and superior memory performance[14] and enhanced auditory processing. Musical activities modulate the expression of genes involved in dopamine signaling, neurogenesis, synaptic transmission, and motor coordination in the brain. During musical performance, genes related to the regulation of dopamine and neuronal communication are greatly modulated, including SNCA and GATA2 genes. The molecular modifications indicate that musical learning over time can bring about permanent adaptations at a neurobiological level.

In animal research, there have been substantial contributions to the understanding of the molecular mechanisms of auditory stimulation[16]. As models for auditory learning, songbirds rapidly express activity-dependent genes when exposed to song. Perception of song is highly correlated with the ZENK gene, which is a transcription factor involved in synaptic plasticity, in auditory processing areas. Likewise, rodent studies show that early exposure to music alters the expression of glutamate receptors in the auditory cortex and anterior cingulate cortex, suggesting long-lasting changes in the expression of excitatory neurotransmission and neural development. The results are consistent with the hypothesis that auditory experiences during critical development periods may regulate neurons' molecular architecture[17].



Figure 01. Animal Studies in Auditory Stimulation Research

The role of music induced neuroplasticity in medicine and rehabilitation is important. There has been a growing use of music therapy in treating neurological ailments like Parkinson's, Alzheimer's, depression, anxiety, stroke and autism spectrum disorders. The mechanisms of action of how auditory rhythmic stimulation helps to enhance motor coordination, decrease stress hormones and cognitive performance are thought to include modulation of neural pathways and gene expression. Furthermore, clinical evidence suggests that music-based interventions can modulate the inflammatory and immune system pathways related to stress, thereby lowering inflammation and enhancing immune function[18]. The therapeutic effects demonstrate the ability of music to be a non-invasive tool that can impact on psychological and biological processes.

The development of molecular neuroscience has increased the scope of interest in transcriptomics and epigenetics of auditory stimulation in recent years[19]. Epigenetic changes can occur to the cell's DNA during learning and/or sensory experience and may affect long-term neural function. Auditory learning has been shown to re-configure the transcriptional profile of the auditory cortex, impacting genes that play a role in memory formation, extracellular matrix interactions and neuromodulatory signaling. These molecular changes could be the reason why repeated musical experiences enhance neural networks and cognitive flexibility over time.

However, there are limitations in the music-induced gene regulation area: there is a lack of well-controlled evidence and clinical trials, and the area is very underdeveloped. Comparisons are made difficult because many of these studies have relatively small sample sizes, a variety of methodologies and a different music exposure protocol. In addition, many human studies use peripheral instead of brain tissue biomarkers. The exact molecular mechanisms involved in how auditory stimuli correlate to neural gene expression are therefore not fully understood. However, recent research has shown that music is a viable and meaningful sensory stimulus that can impact molecular and neural function[20].

The purpose of this research paper is to investigate the impact of auditory stimulation based on music on the expression of genes affecting neural function. Current evidence about the molecular mechanisms, neuroplasticity, neurotransmission and cognitive outcomes of music exposure are reviewed. Genes and signaling pathways modulating synaptic plasticity, learning, memory and emotional regulation are highlighted[21]. The mechanisms may help develop innovative therapeutic uses of music for neurological rehabilitation and mental health improvement.

Research Methodology

This research paper is a qualitative review and analysis of previously published, peer-reviewed literature concerning music based auditory stimulation, neural function, and gene expression. The scientific articles that were relevant to the study were retrieved from databases such as PubMed, Science Direct, Nature, Frontiers, Oxford Academic, and the various journals in the neuroscience field from the year 2000 to 2025. The literature searched for the following keywords: music and gene expression, auditory stimulation and neuroplasticity, music-induced neural function, BDNF and music, transcriptomic effects of music.

The studies included in the review included those that examined the molecular, neurological or genetic effects of music exposure in humans or animal models, as determined by the inclusion criteria. Studies either experimental or review that included information on neural plasticity, activity-dependent genes, neurotransmitter systems, or neurotrophic factors regarding auditory

stimulation were included. Research articles that did not provide information on molecular effects were not analyzed in detail.

Literature collected was grouped into the following themes: gene expression changes, neuroplasticity, activation of auditory cortex, emotional regulation, developmental auditory stimulation, and therapeutic uses. A comparative analysis was performed to determine the genes and neural pathways that have been reported as affected by music exposure. Genes that were specifically targeted included BDNF, ARC, FOS, ZENK, SNCA, and CREB-related pathways because of their importance in synaptic plasticity and memory formation. Secondary information from neuroimaging studies, transcriptomic analysis, and molecular neuroscience research was collated to examine the biological link between the effect of auditory stimulation and neural adaptation.

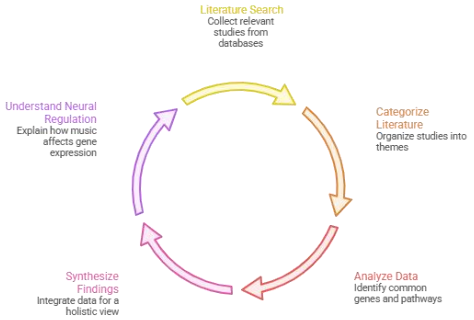


Figure 02. Music's influence on neural function cycle

Results and Discussion

The reviewed works provide a combined evidence that music-induced auditory stimulation produces measurable activity in the nervous system, expression changes in genes and changes in neuroplasticity. Exposure to music affects not only immediate neural response, but also long-term molecular changes that are related to learning, memory, emotional regulation and cognitive performance. These results are in line with the hypothesis that music is a biologically relevant environmental signal that can influence the functions of the nervous system at the molecular and cellular level.

Across the literature, one of the most notable discoveries is that genes are activated in response to auditory stimulation. In studies of songbirds, it was found that after listening to songs, the ZENK gene is quickly expressed in the auditory parts of the brain. ZENK is linked to synaptic plasticity and neural adaptation, suggesting that the perception of sound affects transcription. In mammalian studies, repeated sound exposure resulted in activation of genes like ARC and FOS, which was seen to be similar. The genes are important in the consolidation of memory, in the remodeling of synapsis, and in neuronal communication.

Immediate early genes activation indicates that music can trigger fast neuronal responses that can alter synaptic strength. These molecular changes are basic to learning and the formation of long-term memory. In another auditory cortex transcriptomics study, it was shown that learning an auditory task results in different transcriptomes for memory encoding and cortical plasticity. These results suggest that music-induced neural activity is not transient, but can lead to enduring biological changes which impact cognition and behavior.

Table 1. Effects of Music-Based Auditory Stimulation on Neural Activity, Gene Expression, and Neuroplasticity.

Aspect	Findings	Genes/Mechanisms Involved	Impact on Neural Function
Music-Based Auditory Stimulation	Music exposure produces measurable effects on neural activity, gene expression, and neuroplasticity.	Neural signaling pathways and transcriptional regulation	Enhances neural adaptability and functional brain responses

Immediate Neural Responses	Auditory stimulation triggers rapid neuronal activation.	Activity-dependent genes	Supports quick neural communication and sensory processing
Long-Term Molecular Adaptations	Repeated music exposure causes sustained biological changes in the brain.	Gene transcription and synaptic remodeling pathways	Improves learning, memory, and cognitive performance
Emotional and Cognitive Effects	Music influences emotional regulation and cognitive behavior.	Neuroplasticity-related molecular pathways	Enhances emotional stability and cognitive flexibility
Activation of ZENK Gene	Song exposure rapidly induces ZENK gene expression in songbirds.	ZENK gene	Promotes synaptic plasticity and neural adaptation
Activation of ARC and FOS Genes	Repeated sound exposure activates genes linked to neural communication.	ARC and FOS genes	Supports memory consolidation and synaptic strengthening
Synaptic Plasticity	Music-induced gene activation modifies synaptic strength.	Immediate early genes	Facilitates learning and long-term memory formation
Auditory Cortex Transcriptomics	Auditory learning changes transcriptional patterns in the auditory cortex.	Transcriptional landscapes associated with neural plasticity	Enhances memory encoding and cortical adaptation
Sustained Neural Changes	Music-induced neural activity creates long-lasting biological effects.	Molecular and cellular signaling pathways	Influences cognition, behavior, and brain function over time

Another important result involves the modulation of neurotrophic factors, particularly Brain-Derived Neurotrophic Factor (BDNF). BDNF promotes neuronal survival, dendritic growth and synaptic plasticity. Exposure to music and/or musical training have been shown to increase BDNF expression in several studies. Because music exposure studies were performed on chick embryos, CREB mRNA, CREB-phosphorylated, and BDNF levels were all found to be increased in the hippocampus following auditory stimulation of prenatal chick embryos with music. These molecular changes were linked to better development and cognitive potential of the hippocampus.

This is particularly relevant because CREB signaling pathway controls the expression of genes that are important for neuronal differentiation and long term potentiation. So auditory stimulation of CREB might help to enhance memory and neural connectivity. The results give a mechanism as to why people often see cognitive benefits after being exposed to music training or therapeutic auditory stimulation.

Professional musicians have reported significant transcriptomic differences in association with music performance. Improved expression of genes associated with dopamine signaling, neurogenesis, synaptic transmission and motor coordination were found during musical performance using transcriptome analyses. Genes were especially significant when related to neuronal communication and auditory processing, as in the case of SNCA and DUSP1. The positive emotional and pleasurable effects of listening to music might be attributed to the increased expression of genes that are related to dopamine.

A further connection has been made between music and emotional regulation by the dopaminergic pathways involved. Studies using neuroimaging have shown that listening to music that is enjoyable activates brain areas associated with reward, such as the nucleus accumbens, the ventral tegmental

area and the limbic system. These regions activate in ways that aid in emotional processing, stress reduction, and motivation. Dopamine-related molecular alterations are thus a possible basis for therapeutic effects of music in anxiety disorders, depression, and neurological rehabilitation.

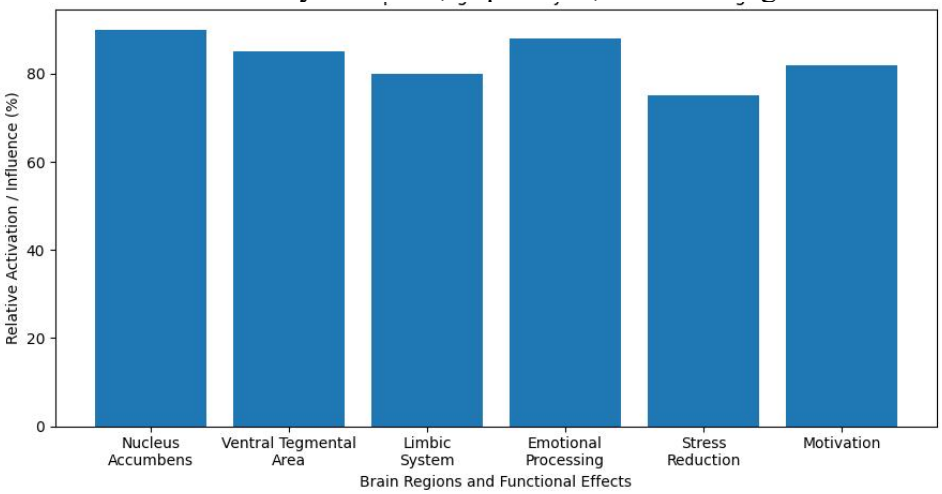


Figure 3. Effect of music on dopaminergic pathways and emotional regulation

Animal studies also indicate that early music exposure can influence excitatory neurotransmission. Musical exposure during development resulted in changes in expression of GluR2 proteins in the auditory cortex and anterior cingulate cortex in rats. The AMPA glutamate receptor is a major component of the GluR2 receptor, which is important for synaptic transmission and neural excitability. Auditory experiences during development can influence the development of neural circuits and maturation of the cortex, as evidenced by changes in GluR2 expression.

The molecular results are complemented by functional neuroimaging data, which show widespread activation of neural systems during listening that is important to music. Research shows that the brain responds both differently and similarly to music and speech. Music stimulates the auditory areas and also invokes emotional, motor and memory circuits. Familiar or emotionally salient music results in increased neural modularity and connectivity in whole-brain network analyses. The results are consistent with the idea that music is conducive to the synchronisation of neural communication within multiple functional systems.

Another large topic of conversation is therapeutic uses of music for auditory stimulation. Music therapy has been beneficial in individuals with Parkinson's disease, Alzheimer's disease, stroke, autism, mood disorders. Rhythmic auditory stimulation could enhance gait synchronization and motor control in PD by stimulating sensorimotor neural pathways. Likewise, music interventions in cognitive disorders seem to influence genes involved in inflammation, neuroprotection and synapse plasticity.

Table 2. Neural Activation and Therapeutic Effects of Music-Based Auditory Stimulation on Brain Function and Gene Regulation.

Category	Music-Induced Neural Response	Associated Brain Regions / Genes	Therapeutic or Functional Outcome
Neuroimaging Findings	Large-scale neural activation during music listening	Auditory cortex, cortical networks	Enhanced sensory and cognitive processing
Auditory Processing	Shared and distinct responses between music and speech	Cortical auditory pathways	Improved auditory discrimination and perception
Emotional Processing	Activation of emotional and reward systems	Limbic system, nucleus accumbens	Better emotional regulation and stress reduction
Motor Function	Engagement of movement-related	Motor cortex, sensorimotor	Improved coordination and gait

	neural circuits	pathways	synchronization
Memory Function	Activation of memory-related networks	Hippocampus, prefrontal cortex	Enhanced memory retention and recall
Neural Connectivity	Increased neural modularity and communication	Whole-brain functional networks	Stronger neural integration and adaptability
Parkinson's Disease Therapy	Rhythmic auditory stimulation improves motor control	Dopaminergic and sensorimotor pathways	Better walking rhythm and balance
Alzheimer's Disease Therapy	Music supports cognitive preservation	Neuroprotective genes and synaptic pathways	Reduced cognitive decline
Autism and Mood Disorders	Music improves emotional and social responses	Limbic and emotional regulation networks	Reduced anxiety and improved interaction
Gene Regulation Effects	Modulation of inflammation and plasticity-related genes	Neuroprotective and synaptic plasticity genes	Supports neural repair and long-term brain health

There is also molecular evidence that supports the anti-stress and immune system properties of music. There are many scientific studies that have documented the ability of music to lower cortisol and affect genes related to immune regulation and inflammatory response. Lower levels of stress hormones may have an indirect beneficial effect on the health of the brain and nervous system because chronic stress has a negative impact on hippocampal plasticity and cognitive function. Music induced relaxation is thus a psychological and biological protective mechanism.

While promising results have been obtained, there are some restrictions to current research. Peripheral blood markers are used in human studies in the absence of direct neural tissue analysis, which is ethically and technically challenging. Comparisons between studies are also hampered by differences in musical genre, length of exposure, the age of the participants and experimental design. In addition, it is still unclear if molecular changes are due to music or emotional/attentional processes of listening.

Another drawback is the fact that gene-environment interactions are complex. One's experiences prior to that music, his/her emotional connections, his/her cultural background, and his/her personal preferences all affect music perception. As such, the reaction of the gene expression to the auditive stimulus can be very different from person to person. Further studies combining transcriptomics, neuroimaging, electrophysiology and behavioural measures may help shed light on these complex interactions.

The reviewed evidence provides strong support that music-based auditory stimulation affects the neural function through molecular, genetic, and neurophysiological mechanisms. Exposure to music triggers the activation of genes involved in synaptic plasticity, neuroprotection and neurotransmission and improves the functional connectivity of brain networks. Such molecular changes are thought to contribute to enhancements in memory, cognition, emotional function and motor coordination in both healthy and clinical populations.

Conclusion

Auditory stimulation via music is a potent sensory stimulation which can modulate neural function at the physiological and molecular level. The results presented in this paper indicate that music exposure has the potential to modify the expression of genes related to neuroplasticity, memory formation, emotional regulation and cognition performance. Immediate early genes like ARC, FOS and ZENK, as well as neurotrophic factors like BDNF, are essential for the neural adaptations caused by music. These molecular modifications facilitate synaptic plasticity, neuronal communication and long-term neural remodeling. There is consistent experimental evidence in human and animal models that music engages widely distributed neural networks that include the

auditory cortex, the hippocampus, the limbic system, and the prefrontal cortex. Musical training and listening to music affect the transcription of pathways related to dopamine signaling, neurogenesis, neurotransmission and stress regulation. These biological reactions can help to account for the positive impacts of music on learning, emotional health, memory, and neurological rehabilitation. These findings have very important therapeutic implications. Music therapy (MT) interventions might be opportunities for non-invasive, cost-effective practices for managing neurological and psychological conditions such as Parkinson's disease, Alzheimer's disease, depression, anxiety and development disorders. Music therapy can positively affect neural plasticity and gene regulation, making it a promising way to boost cognitive resilience and improve the quality of life for individuals' affected by it. While there is strong evidence in the current literature for the connection between music and neural gene expression, further research is needed to better understand the molecular mechanisms. Further research in the fields of genomics, neuroimaging, epigenetics, and auditory neuroscience might shed additional light on the impact of music on the functioning of the human brain in the future. Comprehending these mechanisms may help in the creation of novel therapeutic approaches involving music use as a scientifically validated means to neural health and cognition improvement.

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