Neural Mechanisms of Music in Alleviating Fatigue: Roles of the Autonomic Nervous System, Brain Networks, and the Reward System

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Abstract. With the accelerating pace of modern society, mental fatigue has become a significant issue that affects the physical and psychological health of a wide range of populations. Mental fatigue not only leads to declines in cognitive performance, reduced mood, and decreased motivation, but is also closely associated with increased accident risk, reduced productivity, and impaired athletic performance. Although traditional mitigation strategies-such as behavioral interventions, pharmacological treatments, or exercise-based approaches-have been widely used, they often involve limitations, including potential health risks, high costs, context dependence, or reductions in intrinsic motivation. In recent years, music intervention has emerged as a non-invasive, low-cost, and safe approach that shows considerable potential for alleviating mental fatigue. Based on literature retrieved from the PubMed, Web of Science, and CNKI databases, and incorporating recent advances in neuroscience, this study systematically summarizes the core neurophysiological mechanisms through which music intervention mitigates mental fatigue. Evidence suggests that music intervention may operate through three interacting levels. First, at the peripheral physiological level, music can regulate the autonomic nervous system by suppressing sympathetic activity and enhancing parasympathetic activity. This process improves cardiovascular function and reduces physiological load. Second, at the central neural level, music may promote brain network reorganization. It optimizes functional connectivity within the prefrontal-limbic system and modulates activity in the anterior cingulate cortex (ACC), which improves attentional control and cognitive processing efficiency. Third, at the neurotransmitter level, music can activate the mesolimbic dopaminergic reward system. This activation improves emotional states and enhances motivation, thereby directly counteracting neurochemical changes associated with mental fatigue. These three levels of mechanisms interact and reinforce each other, forming an integrated neurophysiological recovery model. This model provides a systematic explanation for the combined effects of music intervention in enhancing cognitive function, regulating emotions, and promoting physiological recovery. The present study not only advances the theoretical framework of music-based interventions for mental fatigue but also provides practical insights for clinical applications, daily health management, and the use of music interventions in specific operational environments.

Keywords: Mental fatigue, Music intervention, Autonomic nervous system, Dopaminergic reward system, Neurophysiological mechanisms.

1. Introduction

With the rapid development of social economy and the accelerating pace of life, mental fatigue has become a critical issue affecting the physical and mental health of a broad population. As a psychobiological state induced by sustained and prolonged cognitive tasks (Ding et al., 2024; Farrally et al., 2003), mental fatigue not only leads to depressive tendencies such as low mood, diminished interest, and loss of confidence in life in individuals, but also significantly impairs performance in daily work and various activities. It is closely associated with an increased risk of traffic accidents (Borghini et al., 2012), reduced productivity (Tanabe et al., 2007), and impaired athletic performance (Campbell & Moran, 2014; Ding et al., 2024). Prolonged exposure to this state may even pose a potential threat to social harmony and public security stability.

At present, traditional alleviation approaches such as behavioral, physiological, and psychological strategies have been widely applied (Proost et al., 2022), yet they generally suffer from drawbacks

including health risks, situational limitations, high costs, or impaired intrinsic motivation. For physiological interventions, excessive caffeine intake is prone to trigger cardiovascular complications (Nawrot et al., 2003), and inappropriate dosages of creatine supplements may increase renal burden (Kreider et al., 2017). Psychological strategies based on external motivation may reduce an individual's intrinsic motivation (Deci & Ryan, 2008; Ryan & Deci, 2000). Among these, exercise intervention has particularly prominent limitations: improper control of exercise load may instead increase physical fatigue, forming a vicious cycle of "mental-physical" dual fatigue. In recent years, music intervention, as a safe, convenient, and low-risk non-invasive therapy (Martin et al., 2018; Proost et al., 2022; Sun et al., 2024), has gradually gained attention in the field of mental fatigue alleviation. Numerous studies have confirmed that music can counteract mental fatigue from core dimensions such as perceived exertion, motivation arousal, and attention regulation by stimulating dopamine transmission and modulating the activity of the anterior cingulate cortex (Marcora et al., 2009; Pan et al., 2024), and it has achieved remarkable effects in improving mood, reducing fatigue perception, and enhancing performance in related tasks (Fortes et al., 2022; Guo et al., 2015a; Terry et al., 2020).

However, several important limitations remain in the current literature. On the one hand, most studies primarily focus on validating the effectiveness of music interventions. There is still a lack of systematic integration regarding how specific factors—such as music type, intervention duration, and intervention frequency—affect the neurophysiological mechanisms and psychological pathways underlying mental fatigue (Marcora et al., 2009; Sun et al., 2022). On the other hand, different musical styles show substantial differences in their effectiveness for alleviating mental fatigue (Gao et al., 2023; Guo et al., 2015a; Jacquet et al., 2021). In addition, the application of music interventions in many specific contexts remains largely unexplored (Ding et al., 2024; Pan et al., 2024), and standardized application protocols have not yet been established.

Based on these considerations, the present study reviews relevant literature published over the past decade in the PubMed, Web of Science, and CNKI databases. It also incorporates recent advances in neuroscience. The study systematically integrates the core mechanisms through which music interventions alleviate mental fatigue and clarifies the applicability of different music types and intervention strategies across various scenarios. By doing so, this work aims to address the current lack of systematic synthesis in the field. Ultimately, this study seeks to further refine the theoretical framework of music-based interventions for mental fatigue and to provide more targeted and practical theoretical foundations and implementation strategies for clinical practice, daily health management, and applications in specialized domains.

Search terms: (“Music therapy" OR "Musical therapy" OR "Music-based therapy" OR "Music" OR "singing" OR "sing" OR "auditory stimulation" OR "music therapy measure" OR "music therapy assessment" OR "music therapy assessment measure" OR " music therapy outcome" OR "music therapy outcome measure" OR "music therapy rating" OR "music therapy scale" OR "music therapy rating scale" OR "songs" OR "Sound Therapy" OR "music medicine interventions" AND “Mental Fatigue” OR “Mental Fog” OR “Fog Mental” OR “Brain Fog” OR “Fog Brain” OR “Fatigue Mental” OR “Cognitive Weariness” OR “Cognitive Weariness” OR “Weariness Cognitive” OR “Cognitive Exhaustion” OR “Cognitive Exhaustions” OR “Exhaustion Cognitive”)Form CNKI, PubMed, Scopus, EBSCOhost databases.

2. Neurophysiological Mechanisms of Music Intervention in Alleviating Mental Fatigue

Music intervention may alleviate mental fatigue through an integrated neurophysiological recovery mechanism. This mechanism involves three interacting components: autonomic nervous system regulation, brain network reorganization, and activation of the dopaminergic reward pathway. Mental fatigue is typically characterized by reduced neural efficiency in the prefrontal cortex, disrupted functional connectivity between brain regions, increased sympathetic nervous system

activity, and decreased dopaminergic signaling. These changes lead to impaired cognitive performance, deteriorated emotional states, and heightened subjective fatigue (Li et al., 2009; Li & Jiang, 2011; Li & Zhang, 2015). Previous studies indicate that music stimulation can modulate these abnormal states at multiple neural levels. It promotes cognitive and emotional recovery and produces significant anti-fatigue effects (Wang et al., 2023; Liu et al., 2025; Sun et al., 2024).

2.1. Regulatory Effects at the Peripheral Physiological Level

At the peripheral physiological level, music can regulate the activity of the autonomic nervous system. It suppresses sympathetic activity while enhancing parasympathetic activity, thereby shifting the autonomic balance toward a more restorative state. This optimization of autonomic balance improves cardiovascular function, accelerates the recovery of heart rate and blood pressure, and reduces physiological stress levels (Lv, 2022; Zhang & Zhao, 2016).

Specifically, relaxing music can regulate emotional states, reduce feelings of tension and fatigue, and improve heart rate variability (HRV) indices, which facilitates the recovery from mental fatigue (Li & Zhang, 2015). Different musical tempos play distinct roles in this process. Slow-tempo or relaxing music can reduce psychological stress by lowering heart rate and blood pressure. During the recovery phase, slow-tempo music or music-based heart rate training can promote physiological recovery by relaxing the body and enhancing blood circulation (Li & Jiang, 2011; Lv, 2022).

From a mechanistic perspective, music influences neural transmission pathways that involve the brainstem reticular formation and the limbic system. This process promotes endorphin synthesis, inhibits the release of adrenocorticotropic hormone (ACTH), and reduces sympathetic nervous system excitability. As a result, heart rate and respiratory rate decrease, blood pressure is reduced, and skeletal muscle tension declines (Li & Wang, 2006). Improved autonomic stability reduces the physiological resources required for sustained cognitive tasks, thereby lowering the physiological burden associated with mental fatigue.

2.2. Regulatory Effects at the Central Neural Level

At the central neural level, music can influence cortical excitability and the dynamic organization of large-scale brain networks. Mental fatigue is often associated with increased low-frequency electroencephalographic (EEG) activity and elevated neural synchronization, which typically reflects reduced neural processing efficiency. Music stimulation may promote cortical desynchronization, enhance neural network flexibility, and optimize the functional connectivity within the prefrontal–limbic system. A study on brainwave-based music reported that game-state brainwave music reduced functional connectivity among the prefrontal, frontal, parietal, bilateral temporal, and occipital regions in the beta frequency band. This effect helps suppress the abnormal enhancement of interregional connectivity observed during fatigue states and thereby regulates mental fatigue (Guo et al., 2015). In addition, listening to music facilitates a shift in brain activity toward a desynchronized state, which is associated with improved cognitive performance and reduced fatigue. This effect is reflected by decreases in the power of δ, θ, and α waves. At the same time, the recovery of the individual alpha peak frequency (iAPF) suggests that music may play a critical role in alleviating mental fatigue and enhancing cognitive function (Proost et al., 2022). The anterior cingulate cortex (ACC) plays a central role in this process. The ACC is involved in attentional regulation and is also a key brain region through which mental fatigue influences behavioral performance (Posner et al., 2007). Mental fatigue impairs attentional control, and the neural processes underlying attentional control and mental fatigue overlap within the ACC. This overlap suggests that attention may mediate the relationship between mental fatigue and performance (Sun et al., 2022). Music can modulate the perception of pain and fatigue through its effects on the ACC (Antioch et al., 2020). By optimizing functional connectivity within this region, music may help restore executive control and information integration, thereby improving the decline in cognitive function caused by prolonged cognitive load (Sun et al., 2024).

2.3. Regulatory Effects at the Neurotransmitter Level

At the neurotransmitter level, music can activate the mesolimbic reward system and promote dopamine release. Mental fatigue is closely associated with reduced dopaminergic function and decreased motivation. Recent neurobiological models provide an important explanation for this relationship. Mental fatigue activates the anterior cingulate cortex (ACC). This activation increases adenosine transmission and, in turn, reduces dopamine transmission. As a result, individuals perceive greater effort and experience reduced motivation, which ultimately leads to subsequent performance decline (Marcora et al., 2009; Martin et al., 2018). Martin et al. further extended this hypothesis by suggesting that the accumulation of adenosine suppresses dopamine release in the ACC, thereby reducing motivation or willingness to exert effort (Sun et al., 2021).

The role of music at this level is particularly important. Listening to music can stimulate dopaminergic transmission. Because dopamine and adenosine transmission interact with each other (Martin et al., 2018), music listening may reduce perceived effort and compensate for motivational decline, thereby potentially counteracting mental fatigue. Pleasant experiences induced by music are associated with dopamine release in the brain's reward system. This dopamine release is linked to improvements in mood and motivation, which in turn facilitate the recovery of cognitive function (Proost et al., 2022). Therefore, some researchers have proposed that recovery strategies targeting the dopaminergic system, such as music and caffeine, may be effective in counteracting mental fatigue (Fortes et al., 2022). However, compared with nutritional supplements such as caffeine, which may involve sleep disturbance or economic costs, music has advantages as a non-invasive, low-risk intervention with immediate effects and high cost-effectiveness (Li et al., 2013; Sun et al., 2024).

A large body of research has supported this mechanism at the behavioral level. Music can increase arousal, improve emotional state, and enhance exercise motivation and self-confidence, thereby counteracting fatigue and improving performance (Li & Wang, 2006). Playing music during exercise can influence mood, help individuals maintain a more positive mental state, reduce psychological stress, and thus alleviate fatigue (Lv, 2022). As a pleasurable stimulus, music is often prioritized by the brain during sensory processing. To some extent, it may interrupt the ascending transmission of aversive bodily fatigue signals until physical fatigue exceeds a certain threshold, thereby prolonging exercise duration (Li et al., 2013). In terms of emotional regulation, music not only extends exercise duration without aggravating physical fatigue, but also produces positive effects on mood regulation (Li et al., 2013). Different types of music may play different roles in this process. Self-selected music may more effectively reduce mental fatigue because it provides a more pleasant auditory experience, whereas fast-tempo music may reduce subjective fatigue by increasing mental arousal (Li & Jiang, 2011). By enhancing reward system activity, music can improve emotional state and increase intrinsic motivation and task engagement. Improvements in emotion and motivation not only directly reduce subjective fatigue, but may also produce a cross-system synergistic recovery effect by modulating prefrontal function and autonomic nervous system activity (Li, 2013).

2.4. An Integrated Model: Synergistic Effects of the Three Mechanisms

In summary, music intervention may alleviate mental fatigue through the coordinated action of three pathways: autonomic nervous system regulation, brain network reorganization, and activation of the dopaminergic reward system. Together, these pathways form a multi-level neurophysiological recovery model. These three mechanisms do not operate independently. The stabilization of the autonomic nervous system provides a physiological foundation for efficient central nervous system functioning. Brain network reorganization, particularly the functional optimization of the anterior cingulate cortex (ACC), enhances attentional control and cognitive processing efficiency. Activation of the dopaminergic reward system, through dopamine–adenosine interactions, directly counteracts the core neurochemical changes underlying mental fatigue at the levels of motivation and emotion. These three mechanisms interact with and reinforce one another, together constituting the integrated neurophysiological basis through which music alleviates mental fatigue. This model provides a

systematic neurobiological explanation for the comprehensive effects of music intervention on cognitive improvement, emotional regulation, and physiological recovery.

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