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Neural correlates of Music Listening and Recall: Implications for Music-Based Interventions

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ABSTRACT:

Music listening and recall activate several interconnected brain networks, particularly regions involved in sensory, motor, cognitive, emotional, reward and memory processes. Recent studies suggest that engagement with music may modulate dopaminergic and serotonergic systems, enhancing emotion regulation and stimulating neural pathways linked to memory and motor functions. Moreover, evidence suggests that activation of the reward system in response to pleasurable or emotionally significant music may have an impact on memory consolidation. With a focus on studies that examine how music affects brain regions linked to cognition, emotion, and memory, this thesis explores the body of current neuroscientific research. Furthermore, individual differences in white matter microstructure have been investigated as a predictor of variations in music reward sensitivity, offering more proof of the connection between higher-order cortical regions and the reward system in music-induced pleasure. The thesis looks at recent neuroscientific research on the effects of music on the brain and speculates how this information may be applied to create more specialized and successful music-based interventions (MBIs). Whereas it has been shown that music based therapies improve clinical populations' memory and general well-being, more comprehensive, neuroscience-based research is needed to confirm their effectiveness and create standardised, evidence-based methods. By expanding neuroscientific research on music and MBIs, more accessible, affordable, targeted and effective interventions can be developed.

INTRODUCTION:

Music is a complex stimulus that activates, and has an impact on several brain mechanisms. The field of music neuroscience investigates how music impacts the brain by conducting experiments using neuroimaging, behavioural testing, and physiological measures to understand its effects on several brain processes. While existing literature has established associations between music and several brain functions, there is a need for more scientifically rigorous studies that offer a further exploration, from a neuroscientific approach, of how music affects memory. Music has been observed to activate auditory, motor, cognitive, emotional, motivational, reward and memory-related brain systems, with some of these being engaged simultaneously.

As a consequence of an interaction between the auditory cortex and the hippocampus during music evoked memory retrieval, music and memory have been associated. This indicates that music may have an impact on memory functions, possibly in a beneficial way.

Furthermore, research has suggested that music can induce neuroplastic changes in brain regions and pathways, potentially improving their long term functioning. The role of the reward system in modulating memory mechanisms is of particular interest in this thesis, with dopamine-sensitive structures, such as the putamen, amygdala, and ventral striatum having an impact on music-induced pleasure and memory consolidation.

I highly support further developments of music-based interventions (MBIs). Music is generally affordable and easily accessible, which makes it an ideal tool to use in therapy. Music therapy (MT) has been shown to facilitate positive outcomes for example Alzheimers and Parkinsons disease patients, with the first mentioned showing improvements in memory function and the latter showing motor improvements in response to MT. These findings hold promise for music therapy as an alternative to traditional pharmacological treatments. Moreover, music therapy might be beneficial for individuals suffering from neurodevelopmental disorders such as attention-deficit hyperactive disorder who often struggle with emotion regulation, attention, and working memory. Research revealed that individuals with ADHD, who received music therapy, showed significant improvements in both neurophysiological and psychological outcomes after treatment.

In this thesis I will focus on a comprehensive investigation about how music affects different brain structures and functions, particularly processes involved in perception, cognition, emotion, reward, and memory. I will look at the neural mechanisms involved in music perception, emotion and memory, while looking at recent studies that have associated music with memory and reward-related brain systems. Finally, I will evaluate the potential of MBIs and propose future directions for further research. The aim is to deepen the understanding of neuroscientific mechanisms involved in music listening, to promote the development of novel, more targeted and effective MBIs.

CHAPTER 1-NEURAL ASPECTS OF MUSIC PERCEPTION AND MEMORY

1.1 Music Processing in the Brain

Music perception involves several brain areas and is not solely auditory, but also involves motor regions. A study by Zatorre et al. (2007) investigated music perception and production while explaining how auditory and motor systems are functionally connected.

The process of music perception involves the engagement of specific auditory processing pathways starting with the primary-auditory cortex (A1) which processes basic sound features like frequency and intensity. This allows individuals to break down and identify elements of novel sounds, enabling the brain to differentiate between different tones and pitches. Following this, the sound is processed further in higher-order auditory regions, including the superior temporal gyrus (STG), which is involved in analysing pitch and the superior temporal sulcus (STS), which is involved in processing the temporal aspects of sound. These higher-order areas help in recognizing musical patterns (Zatorre et al., 2007). In addition to this, the study proposes the dual-stream model of auditory processing, which divides the auditory pathways into two streams. The dorsal stream, which connects the auditory cortex with motor regions to integrate auditory information with motor actions, and the ventral stream which originates in A1 and projects to the anterior temporal lobe (ATL) and inferior frontal cortex (IFC), which then work together to analyze and classify sounds. Another study also emphasizes the importance of the motor-auditory interaction, suggesting the dorsal stream's role in auditory-motor mapping, and the ventral stream's role in pitch perception and memory (Loui, 2015).

A recent review article further explored how music engages and affects the brain, while emphasizing how individuals, when listening to music, actively generate predictions about what may happen next. This has induced a more comprehensive understanding of how music processing involves brain structures involved in perception, action, emotion and learning (Vuust et al., 2022). Music brain networks have been identified by using electrophysiological and neuroimaging techniques, such as, electroencephalography (EEG), magnetoencephalography (MEG), and functional MRI (fMRI). The key brain regions that have been identified to be involved in music perception include the A1 and auditory cortices, with melody perception activating regions that are specialized for other purposes than audition, such as motor, emotional and cognitive processes. Moreover, music action and perception have been shown to become engaged even without stimuli, that is when individuals use mental imagery (Vuust et al., 2022). Music action, such as singing or moving to music, engages the motor cortices, premotor cortices, inferior frontal gyrus (IFC), basal ganglia and the cerebellum. These regions work together to integrate sensory input with motor actions. Brain regions involved in emotional processing also become activated during music engagement. These include the orbitofrontal cortex (OFC), insular cortex, cingulate cortex, ventral tegmentum area (VTA), hypothalamus, nucleus accumbens (NAcc), ventral pallidium and the amygdala (Vuust et al., 2022). Each of these regions serve different purposes, with the OFC evaluating and assigning value to stimuli, the insula being involved in awareness and emotional salience, the cingulate cortex contributing to emotion regulation and attention, the VTA being a key source of dopamine involved in motivation and reward, the hypothalamus mediating physiological responses to emotion, and the NAcc processing reward and pleasure (Koelsch, 2014). Activation of these regions may lead to the subjective pleasure and emotional elevation individuals often experience when listening to music (Reybrouck & Van Dyck, 2024).

Supporting this, additional neuroimaging studies of music and emotion have demonstrated that music perception activates emotion-related brain networks and that music engagement may modulate activity in limbic and paralimbic brain structures, including the amygdala, NAcc, hypothalamus, hippocampus, insula, cingulate cortex and OFC (Koelsch, 2014). Moreover, intense emotional responses to music have been observed to trigger a dopamine (DA) release in the striatal system (Vuust et al., 2022). This aligns with more recent findings which further confirm that listening to music can stimulate the reward system, including brain regions such as the NAcc, insula, and the orbitofrontal cortex (OFC) (Reybrouck & Van Dyck, 2024). Interestingly, music perception mechanisms have been compared between musicians and non-musicians, with results revealing differences in brain structure and function involved in motor and auditory regions between the two groups (Gaser & Schlaug, 2003). This suggests music's potential ability to modulate brain structure and function through a process called neuroplasticity.

1.2 Music and Memory Processes

The brain's ability to perceive music also depends on memory processing functions. Memory allows individuals to identify previously heard tunes and associate music with their past experiences and emotions. The brain requires memory processes to interpret musical stimuli because these processes handle storage and recall functions during musical responses. Neuroscience describes memory as a cognitive process that progresses through multiple stages. The memory process involves encoding, consolidation, storage and retrieval stages which operate through different neural systems that each independently affect information processing and recall.

The most important brain regions involved in memory processes are the hippocampus, prefrontal cortex (PFC), and the temporal lobes. A study by Eichenbaum (2017) investigates how these areas interact in memory processes, providing a good overview of memory. According to the author, the first stage of memory formation is encoding. In this stage sensory input is processed and transformed for storage. The hippocampus is mostly responsible for integrating and organizing the new incoming information, while the PFC directs our attention and helps to make sense of this information. The temporal lobes are then involved in the storage and retrieval of these memories. These brain regions work together to enable the encoding, storage, and eventual recalling of past experiences, which also includes musical associations (Eichenbaum, 2017). Memory processes might influence music perception while music may also impact memory functions. A study by Janata (2009) investigated the mechanism by which familiar music stimulates the retrieval of autobiographical memories, which consist of personal recollections from individual experiences, by examining brain functionality during music processing using functional magnetic resonance imaging (fMRI). The study identified the medial prefrontal cortex (mPFC) high importance in connecting music to memories, particularly when participants listened to songs that held personal or emotional significance for them, leading to stronger activation in this region. The investigation revealed that the hippocampus works with the auditory cortex to recover memories through music which combines sound elements with both emotional and contextual memory aspects. These collaborative brain functions enable people to record and retain musical information that may connect to prior emotional, or life experiences (Janata, 2009). When short-lived memories are transferred into long-term storage, which happens when we sleep or rest, the hippocampus works on strengthening and storing the neural patterns generated during the initial experiences (Squire & Wixted, 2011). These findings indicate that music can serve as a powerful trigger for autobiographical memory retrieval even for those with memory impairments (Jakubowski & Ghosh, 2019).

Furthermore, listening to emotionally significant music can have an impact on the reward circuitry by activating dopaminergic pathways, namely in the striatum, ventral tegmental area (VTA), NAcc, amygdala, and the PFC. While current studies lack the direct investigation of the impact of this on memory, dopamine is believed to enhance memory consolidation, especially for emotionally salient events (Lisman & Grace, 2005).
Together these findings suggest that music holds the ability to amplify emotional aspects of experiences and form stronger neural links resulting in enhanced memory recall.

CHAPTER 2-NEUROSCIENTIFIC EVIDENCE OF MUSIC AND MEMORY

2.1 The Neural Correlates of Music Listening and Recall

Evidence suggests that music engages both auditory and motor systems simultaneously (Zatorre et al., 2007). To map out the brain regions and identify the most important neural mechanism involved in music listening and recall we refer to a study conducted by Ding et al. (2019). The study consisted of 10 epilepsy patient participants, with researchers analyzing neural activity in different brain regions connected with music listening and recall using electrocorticography (ECoG). The study specifically investigated how these brain regions represent the time course and temporal features of music during listening and recall. Two time windows were used for ECoG signal analysis by experimenters, the onset (0-500 ms) and sustained phase (after 500 ms). The onset phase consisted of participants listening to familiar instrumental music which showed significant high-gamma responses across the cortical areas. Researchers recorded the peak gamma responses in the right hemisphere's posterior superior temporal gyrus (pSTG). The right hemisphere demonstrated elevated high-gamma activity across the bilateral supramarginal gyrus (SG), temporal lobe, superior frontal gyrus, precentral gyrus (PG), and right inferior frontal gyrus (IFG). However, statistically significant responses were limited to the superior temporal gyrus (STG), PG, IFG, and superior frontal gyrus.

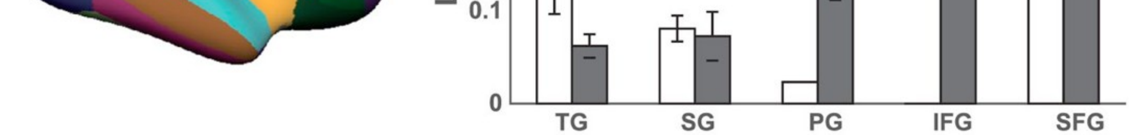
This observed activation of brain regions during music listening reflects a bottom-up processing mechanism, with sensory input initially analyzed in auditory areas (pSTG) and then integrated with motor and cognitive systems (PG and IFG).

The sustained phase neural recordings demonstrate neural activity that persists beyond the initial onset period which occurs after the 500 ms mark, illustrating sustained brain activity during active music processing. The researchers assessed this phase through the calculation of inter-trial coherence (ITC) values across diverse frequency bands which represent distinct brainwave activities. By calculating ITC they could measure how consistent the brain's electrical responses were across repeated presentations of the same musical stimuli.

Findings revealed that the most consistent neural signals during music listening in the delta band were located in the right pSTG. This suggests that the pSTG plays a role in maintaining the rhythm and timing of musical input. Significant consistency was found in electrodes placed over the bilateral pSTG, especially in the right hemisphere, along with the right PG and the right IFG.

These results suggest that music listening triggers the activation of sensory and motor cortical areas in a regular and time-dependent manner. Furthermore, neural activity in the right STG tracked the changes of the music intensity over time. Electrodes in this area showed especially strong correlations between high-gamma activity and the dynamic intensity of the musical stimuli. This suggests the right pSTG high sensitivity to detect changes in the loudness or intensity in music over time. High-gamma activity appears to reflect the brain's real-time tracking of auditory input, supporting the view that music perception involves a widespread and ongoing neural synchronization.

During the recall phase of the study researchers instructed participants to mentally replay familiar musical pieces. The high-gamma responses began in the IFG and the PG before expanding to the temporal regions including the pSTG during this phase. The observed reversed neural activation pattern indicates a processing shift from bottom-up to top-down when handling musical stimuli. This indicates that cognitive and motor planning regions establish internal music representations prior to activating auditory brain areas. During the sustained recall phase, both delta and high-gamma band responses in the frontal and temporal lobes maintained their correlation with the intensity level of imagined music. During listening tasks the frontal lobe activated before the temporal lobe but during recall tasks the activation sequence reversed. Figure 1 illustrates the latency analysis of EcoG signals during music listening and recall in the right hemisphere, showing how the sequence of brain activation reverses between listening and recall.



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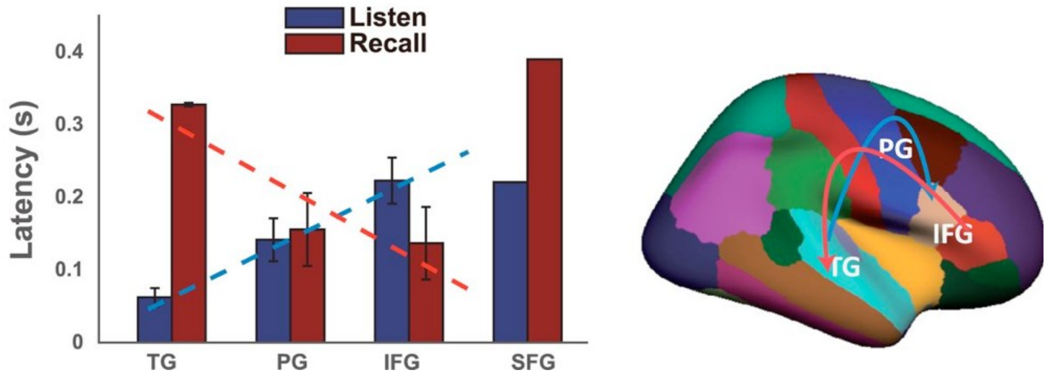

Figure 1. Latency analysis of EcoG signals during music listening and recall in the right hemisphere. Left, During listening (blue bars), latency increased from TG to PG and IFG regions. During recall (red bars), latency decreased from TG to PG and IFG regions. Dashed lines show the linear regression of the latencies across the brain regions for music listening (blue arrow) and recall (red arrow). Right, diagram showing the flow of high-gamma response across cortical regions during listening (blue) and recall (red).

This suggests that higher-order cognitive regions initiate mental replay before the auditory regions become active. These findings align with the idea proposed by Zatorre et al. (2007) that music perception and imagery involve shared auditory-motor networks. They argued how internally generated sound (imagery) engages similar neural circuits as the actual perception of it. Furthermore, auditory-motor interactions have been shown to be guided by both feedforward and feedback processes. This aligns with the findings from Ding et al. (2019) concerning the shift from bottom-up to top-down processing during recall. The evidence presented in this chapter supports the speculation that music listening and recall involve both auditory and motor systems, where internal models in the brain allow higher-order regions to simulate musical experiences and drive vivid auditory imagery even in the absence of sound (Ding et al., 2019; Zatorre et al., 2007).

2.2 Neuroplasticity and Individual Differences in Music Reward Sensitivity

Music has been proven to engage brain regions and functional circuits involved in sensory-motor, cognitive, memory, and emotional processes (Talamini et al., 2022), while also having the ability to modulate brain circuits and trigger a release of various neuromodulators (Zaatar et al., 2023). This is particularly noticeable when looking at neuroimaging evidence, which demonstrates how long term engagement and experiences with music are associated with adaptive structural changes in brain regions involved in auditory processing, motor coordination, and memory. Although a recent study (Zaatar et al., 2023) mainly discusses these adaptations in musicians, the findings reveal important evidence of how music may promote neuroplasticity, which is the process of long term adaptation of brain structures or circuits in response to experiences.

Music is a complex auditory and emotional stimulus which activates various neural systems that are prone to neuroplasticity, including perception, emotion, memory, and attention. Neural plasticity can manifest itself as changing neurons, modification of synaptic weight, synaptic pruning, and cortical remapping. Musical experiences, specifically if they are emotionally engaging or frequent, are believed to promote this modulation of neural structures, especially in musicians who have been playing an instrument from a young age (Zaatar et al., 2023). Furthermore, music can activate cortical and subcortical regions related to reward, memory, and emotion, potentially promoting adaptive changes in neural structures that support these processes. The reorganization of these neural structures may possibly help in promoting memory mechanisms. Neuroimaging studies have found that rewarding experiences of music can adaptively modulate activity and connectivity in regions such as the auditory cortex, hippocampus, and prefrontal areas, including the NAcc (Zaatar et al., 2023). These findings suggest music's ability to reinforce memory consolidation, reward processing, and emotion regulation, as these regions are involved in such processes.

We can therefore speculate that music engagement, especially when frequent and of high emotional valence, may lead to the promotion of neural plasticity, contributing to long-term adaptive changes in the brain's emotional and memory circuits.

Following this, An investigation by Martínez-Molina et al. (2019) explores the relationship between the subcortical reward system and higher-order cortical areas in music-induced pleasure, revealing how individual differences in music reward sensitivity are reflected in white matter microstructure. The purpose of their study was to examine the structural connectivity between the STG, Nacc and OFC in order to comprehend the microstructural characteristics of these pathways and how they affect individual variations in music reward sensitivity. In order to measure their sensitivity to music-related rewards, participants filled out a number of questionnaires, including the Barcelona Music Reward Questionnaire (BMRQ), which has a scoring system that goes from high enjoyment to very low enjoyment. Researchers were able to learn about the white matter architecture in the brain's regions responsible for processing music rewards, including STG, OFC, and NAcc, by using diffusion tensor imaging (DTI) scans. The researchers used T1-weighted MRI scans, which provide detailed, high-resolution images of the brain structure, to pinpoint and guide their analysis of the white matter pathways from the DTI data. After that, researchers compared the DTI scans with the self-reported results from the earlier questionnaires that participants had filled out. This made it possible for them to determine the relationship between self-reported sensitivity to musical reward and individual variations in white matter properties.

The findings showed that lower sensitivity to music rewards was linked to higher values of axial diffusivity (AD) in the rSTG to OFC, which measures how easily water molecules travel along the main axis of white matter fibers. It would appear from this that individuals who self-report having less musical pleasure have altered microstructure in this particular auditory-reward pathway. Similar trends were seen in the left hemisphere's NAcc to OFC tract, where lower BMRQ scores were linked to higher AD values.

These structural findings were also connected to earlier fMRI results that showed a negative correlation between AD and NAcc activation in the NAcc-OFC tract in response to enjoyable music. This implies that people with stronger neural reactions to music have lower AD in this pathway. Figure 2 illustrates the structural connectivity between firstly the STG and OFC in the right hemisphere (Fig. 2A), secondly the Nacc to OFC in the left hemisphere (Fig. 2B), and lastly the Nacc to OFC in the right hemisphere (Fig. 2C) and its correlations with scores from the BMRQ, which indicates music reward sensitivity. Higher diffusivity values were negatively correlated with BMRQ scores, indicating that individuals with lower music reward sensitivity show higher diffusivity in these white matter pathways.

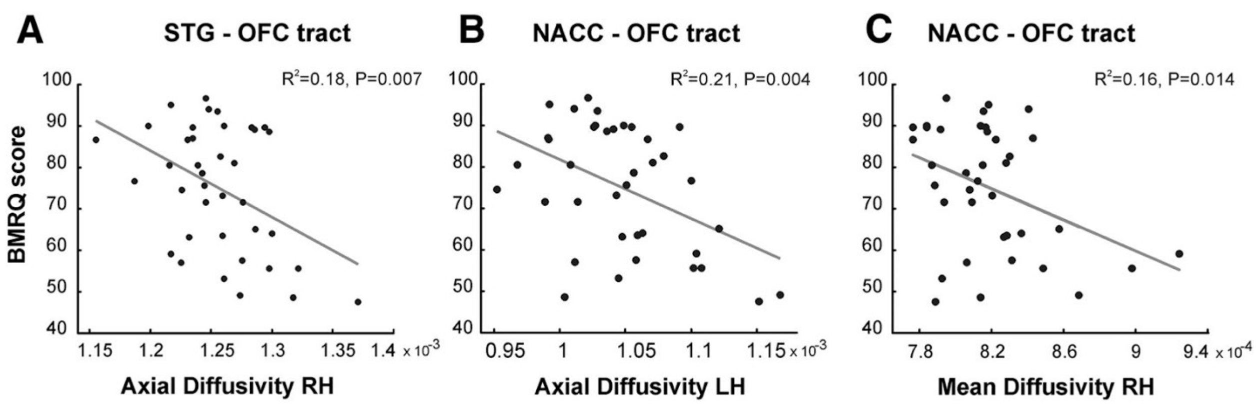

Figure 2. Microstructural properties of the STG-OFC and Nacc-OFC pathways in relation to music reward sensitivity (overall BMRQ scores). A, Right hemisphere AD values in the STG-OFC pathway were negatively correlated with overall BMRQ scores. B, Left hemisphere AD values in the Nacc-OFC pathway were negatively correlated with overall BMRQ scores. C, Right hemisphere mean diffusitivity values in the Nacc-OFC pathway were negatively correlated with overall BMRQ scores.

This clear structure-function relationship suggests that individual variations in the reward-related pathways' microstructure may affect how strongly music is perceived as rewarding. Furthermore, a mediation analysis revealed an indirect pathway from the auditory cortex (STG) to the reward system (NAcc), going through the OFC. This suggests the OFC role in integrating emotional and perceptual aspects of music into the reward circuit (Martínez-Molina et al., 2019), possibly contributing to the emotional and memory-enhancing effects of music. These findings align with the idea proposed by Zaatar et al. (2023), which suggested that musical experiences may promote neuroplastic changes in both brain structure and function.
This growing area of research highlights how music-induced emotional engagement has the potential to shape both neural circuits and cognitive processes, including those related to memory. Moreover, a recent study by Talamini et al. (2022) demonstrated that emotions evoked by music can affect how memories are encoded. According to the study, listening to music with strong emotional content helped participants recognize emotionally charged images more accurately when taking a memory test. When combined with similar emotional content, the emotional tone of music improves memory encoding processes. These results support the more general theory that music affects brain systems related to emotion, perception, and memory. Overall, the evidence in this chapter shows that music can affect individual cognitive and emotional processing through emotional engagement and neuroplastic adaptation, with individual differences in white matter microstructure also playing an important role for determining music reward sensitivity.

2.3 The Interaction Between Music, Reward and Memory Systems

Music and memory are believed to be linked through shared engagement of dopamine-related reward mechanisms. These mechanisms may underlie music's ability to enhance memory processes by activating emotional and motivational systems in the brain (Ferreri et al., 2021). To gain a better understanding of the neural activity involved in music perception and its potential to enhance memory, we will begin by looking at findings from a recent study by Sayal et al. (2024). The study investigates the neural correlates of perceived valence and arousal during music listening, using fMRI and multivoxel pattern analysis (MVPA), a brain imaging technique used to study patterns of activity across multiple brain regions.

Findings revealed that listening to music activates various cortical regions, including the auditory cortex, thalamus, motor regions, and structures associated with reward processing (Sayal et al., 2024). Increased activity was observed in the supplementary motor area (SMA), along with activation in reward-related regions such as the amygdala and putamen. This aligns with previous findings, which suggested that music with high emotional content elicits more significant activation in these regions (Talamini et al., 2022). The putamen, which is involved in the processing of rewards and motivation (Weinstein, 2023), was also activated during music listening. Although Sayal et al. (2024) did not provide a detailed analysis of the putamen's specific role in music listening, its activation likely reflects the pleasurable or rewarding aspects of music.

Building on the findings from Sayal et al. (2024) it is relevant to look at a study conducted by Ferreri et al. (2021). While this study does not examine neural activity directly, it provides important behavioural evidence rooted in neurobiological theories of dopamine's role in reward and memory. Therefore offering important insights for future applications of music-based interventions that might target reward and memory mechanisms.

The study explores how dopamine-dependent musical reward can drive memory improvements. 29 participants completed the study, while after applying exclusion criteria based on familiarity with the musical stimuli, very poor memory task performance, and indications of musical or general anhedonia, the final analyzed sample included 21 healthy individuals. Each participant took part in three different sessions. For each session, they (blindfolded) received a capsule containing either a dopaminergic precursor with an inhibitor of peripheral dopamine metabolism (levodopa, 100 mg+carbidopa, 25 mg), a dopamine receptor antagonist (risperidone, 2 mg), or a placebo (lactose).

Following this, participants completed a series of tasks. Tasks were performed while the drugs were active in the body as the aim was to test how different dopamine levels affected musical memory. They began with a musical memory encoding phase which consisted of listening to 24 unfamiliar instrumental classical music excerpts, while rating how pleasurable and emotionally engaging they were across three successive exposures. Participants gave subjective ratings of pleasure, arousal, valence, and familiarity in the first and third exposures, while the second exposure was intended for passive listening and deeper encoding.

Twenty-four hours later, participants returned for a memory retrieval testing without any drug-intake. They completed a recognition memory task which involved listening to 24 previously heard and 24 new musical excerpts. For each excerpt, participants were demonstrated to specify whether they had heard it before, followed by a remember/know/guess judgement to evaluate the success of memory retrieval. Results revealed that participants generally performed well in the memory task, with no significant differences in overall accuracy between the three conditions. However, participants in the placebo condition better remembered excerpts they had rated as pleasant and arousing compared to those they forgot, suggesting a link between the emotional experience of music and memory recall.

Furthermore findings revealed that the relationship between musical pleasure and memory was influenced by both drug condition, and the participant's sensitivity to musical reward. Risperidone appeared to weaken the positive effect of musical pleasure on memory, but mostly for individuals who had low to medium sensitivity to musical reward. In contrast, for individuals with high music reward sensitivity, the positive effect remained strong despite the dopamine blockade. Interestingly, levodopa did not increase memory performance significantly despite the known role of dopamine in reward and memory systems. Finally arousal levels seemed to enhance memory while this effect was reduced under both drug conditions compared to placebo. Together the studies by Sayal et al. (2024) and Ferreri et al. (2021) provide valuable insights into the neural and behavioural mechanisms that may underlie the relationship between music and memory. Sayal et al. (2024) findings highlight how listening to music activates several cortical brain regions including the auditory cortex, thalamus, SMA, and reward-related structures, which are important for emotional and cognitive processing. This supports the idea that music engages widespread brain networks that may facilitate memory-related functions. Ferrari et al. (2021) study provides behavioural evidence based from existing neurobiological theories, demonstrating how the emotional and rewarding aspects of music, shaped by dopamine levels can influence memory performance. Together these studies provide important evidence suggesting how individual sensitivity to musical reward interacts with dopamine modulation to affect memory (Ferreri et al., 2021; Sayal et al., 2024). We can therefore speculate that music, through its ability to engage both emotional and cognitive brain systems, holds potential as a tool for improving memory.

CHAPTER 3- IMPLICATIONS FOR MUSIC-BASED INTERVENTIONS

3.1 Music-Based Interventions for Neurodegenerative Diseases

According to evidence there seems to be an existing link between music and memory systems (Ferrari et al., 2021). A specific memory system for music itself has even been proposed, which can be preserved in the presence of neurodegenerative diseases that involve memory deficits such as Alzheimer's disease (AD) (Groussard et al., 2019). Further findings indicate that music can potentially be used in clinical practice to improve cognitive functions in patient populations (Bleibel et al., 2023).

Music is easily accessible, which makes it an ideal tool to use in treatment for various health problems. Music therapy (MT) is the use of music and its elements to improve individuals health and well-being (Lyu et al., 2018). MT can involve both active or receptive methods, which should be implemented by a trained music therapist who follows a protocol based on professional standards in MT (Waldon, 2015). The effects of MT on cognitive function and mental well being of AD patients were explored in a recent study (Lyu et al., 2018).

The study included a total number of 298 AD patients with mild, moderate, or severe dementia, which were randomly divided into three groups. None of the participants had professional musical experience before. The three groups consisted of a music therapy (MT) group, a lyrics reading group, and a control group, with each group receiving different interventions for three months. Participants underwent various tests assessing cognitive functions, neuropsychological symptoms, and activities of daily living. The assessment contained the mini mental state examination (MMSE), which assesses multiple domains of cognitive function, including, orientation, registration, attention and calculation, recall, language, and praxis. Additionally the WHO-UCLA AVLT was used to assess participants' short-term and long-term memory by scoring their performance on immediate and delayed recall. Assessments were conducted before the application of the intervention (at baseline), after three months of the intervention, and finally after six months.

The music therapy group received MT by singing or listening to familiar, favorite songs, which they especially enjoyed during their twenties and thirties. The lyrics reading group read the lyrics of familiar, favorite songs without the melody, also from songs they enjoyed during their twenties and thirties. The control group received no special interventions. The MT and lyrics reading activities were carried out twice daily, in groups with one therapist and 5-6 participants. Results revealed that the intervention in the MT group appeared to have positive effects on memory functions, particularly for individuals with mild AD. At the first follow-up assessment (after 3 months), participants in the MT group performed significantly better than the other groups in memory recall tasks of the AVLT, which measured both immediate recall, for short term memory and delayed recall, for long term memory. AD patients in the MT group showed improvements in both types of recall, with patients who had mild AD showing the most noticeable memory enhancements. This suggests that early stage AD patients may benefit the most from MT interventions. However, these positive effects were only observed in the first follow-up and not maintained into the final 6 month follow-up. Despite this, the results show that MT may help enhance short-term memory functions which are crucial for AD patients to allow them to maintain a sense of identity, communicate and improve their daily functioning. Participants in the lyrics reading and control group did not show the same memory improvements, suggesting that music itself contributed to the positive effects observed for the MT group. Moreover, these results support the theory that emotionally salient music may activate preserved memory systems and enhance recall (Groussard et al., 2019), as the music selected for the therapy was personally meaningful for participants.

Furthermore, several studies have investigated the benefits of MT for Parkinson's disease (PD) and other neurological disorders (Brancatisano et al., 2020). As music has the ability to engage multisensory and motor networks, having effects on emotional and reward systems in the brain, it may be used to facilitate therapy and rehabilitation of neurological disorders (Altenmüller & Schlaug, 2013). A recent study demonstrated how a music-based therapy program improved balance and functional mobility in PD patients (Da Silva et al., 2020).

This controlled, non-randomized clinical trial involved 13 PD patients, who took part in an 8 week music-based intervention. Music was mixed with physical therapy, with participants assessments across three time points, namely at baseline, following the intervention, and during a follow-up period without continued therapy. The intervention included 16 sessions, twice a week, of music accompanied physical therapy. In the sessions, participants listened to a playlist containing 18 songs chosen for their regular, predictable rhythmic patterns, while performing physical therapy exercises based on the American Parkinson Disease Association guidelines (American Parkinson Disease Association, n.d.). During sessions, the music serves as an environmental facilitator, guiding external timing cues to help participants initiate and coordinate movements more effectively. This may compensate for the basal ganglia deficits commonly observed in PD (Blandini et al., 2000). Therefore the music is not solely used for motivational purposes, rather it is used as a neurological tool that enhances the auditory-motor pathways in PD patients. Following the intervention, participants showed improvements in balance, functional mobility, and movement coordination. However these improvements had declined again during the follow-up period without continued therapy, implying the importance of sustained engagement of therapy. These findings support the theory that music, rhythmic in this case, can effectively be used to improve motor performance in individuals with PD when used as an external cue.

Together these studies provide evidence on how music-based therapy can be beneficial for both AD and PD patients, improving their quality of life and well-being. The findings revealed how music therapy can enhance memory functions, particularly for patients in the early stages of AD, and improve motor related deficits in PD patients. These results highlight music's ability to engage neural systems involved in memory and motor control, offering an alternative approach to traditional pharmacological therapies.

3.2 Music Therapy for Attention-Deficit Hyperactivity Disorder

Music-based interventions have also been shown to benefit individuals suffering from neurodevelopmental disorders, such as attention-deficit hyperactivity disorder (ADHD) (Park et al., 2023).

ADHD involves characteristics, such as attention deficits, hyperactivity, and impulsivity as major symptoms. These symptoms can overlap with other mood disorder symptoms, such as anxiety and depression (Park et al., 2023), and have been associated with altered serotonin (5-HT) and dopamine (DA) functions (Nikolaus et al., 2021). 5-HT and DA are important neurotransmitters involved in emotional regulation and reward systems. Evidence suggests that ADHD patients have low levels of 5-HT and dysfunctional DA system (Nikolaus et al., 2021) which may contribute to emotional dysregulation and cognitive impairments, including difficulties with attention and working memory (Kofler et al., 2020). As a result individuals who suffer from ADHD often experience reduced quality of life (Park et al., 2023).

Musical pleasure has been shown to enhance memory through dopaminergic pathways (Ferreri et al., 2021; Sayal et al., 2024). Therefore it is relevant to explore how these mechanisms may operate in individuals with ADHD, possibly offering an alternative approach to pharmacological treatments.

Park et al. (2023) investigated the effects of music therapy (MT) for depression in children and adolescents with ADHD. The study randomly assigned 36 ADHD participants to either a MT group or a control group. The MT group intervention involved both active and receptive music therapy twice a week over a period of 12 weeks, while the control group intervention received standard care. Researchers assessed depression symptoms using the Children's depression Inventory (CDI) and changes in depression and stress were tracked by measuring 5-HT secretion and cortisol expression with blood tests both before and after the intervention.

Results revealed significant improvements in both neurophysiological and psychological outcomes for the MT group, with an increase in 5-HT levels after the intervention while the control group did not show such changes.

These findings demonstrate how MT may effectively enhance serotonin activity in ADHD individuals, which can contribute to better emotional regulation and reduced depressive symptoms. This was further supported with lower observed depression scores on the CDI for participants in the MT group (Park et al., 2023). Regarding cortisol level changes, the MT group showed significantly lower cortisol levels after the intervention, while the control group did not, which indicates MT role in stress reduction for individuals with ADHD.

These results are consistent with existing studies that indicate the importance of 5-HT and DA in managing mood and stress (Nikolaus et al., 2021), especially for ADHD individuals who often show dysregulated emotional responses and difficulties with working memory (Kofler et al., 2020).

Together with these findings, we can speculate that MT may effectively modulate the serotonergic and dopaminergic dysfunctions commonly observed in ADHD individuals, improving emotional and cognitive functions, including memory. Music can therefore serve as a therapeutic tool, offering an alternative approach to pharmacological treatments for ADHD.

3.3 Challenges and Future Directions in Research on Music-Based Interventions

Music has been shown to engage several brain areas, while also holding the potential to strengthen brain pathways and networks involved in sensory and motor processes, such as emotion and memory (Reybrouck et al., 2018). Music-based interventions (MBIs) can therefore be considered as a promising therapeutic approach that engages and possibly strengthens these brain mechanisms through neural plasticity (Zaatar et al., 2023), especially for clinical populations that experience symptoms such as memory loss and motor deficits. In contrast to traditional pharmacological treatments, music as medicine, offers a cheaper, more accessible, and less invasive therapeutic treatment (Edwards et al., 2023).

However, for MBIs to be as effective as possible, I believe they need to be studied better in a neuroscientific context. The understanding of brain mechanisms involved in music perception, and how the reward circuitry is involved (Sayal et al., 2024), are of crucial importance to develop more effective and targeted treatments. Moreover, MBIs targeting brain areas for memory enhancement have not been studied in depth despites some indications of short term memory function improvements in studies for patients with mild Alzheimer's disease (Lyu et al., 2018).

Current challenges in this field of research include a lack of data from rigorous, well-powered studies, with data about the beneficial effects of MBIs solely obtained from small scale clinical trials (Edwards et al., 2023). Many studies on the effects of MBIs have not been designed within a scientific and theoretical framework, resulting in inconclusive findings. This significantly impedes the generalizability and reliability of MBIs research findings, reducing their statistical power and the validity of their conclusions.

Additionally current MBIs range from treatments involving passive listening to music making, which makes it difficult to draw broad conclusions or create standardized protocols for treatment. For example, although MBIs including music therapy for AD patients have demonstrated positive outcomes, these results are not always consistent across studies.

Another significant issue in this field of research is the complexity of measuring the effects of music on the brain precisely. Koelsch (2009) argues how music engages several brain networks simultaneously, making it difficult to isolate its effects in a scientifically rigorous way. The interaction between the various brain systems that contribute to the therapeutic benefits of music are therefore difficult to assess without a consistent and clear methodology (Koelsch, 2009).

The lack of neuroscience based protocols for MBIs is another issue, with existing studies focusing more on behavioural outcomes and subjective reports rather than objective, quantifiable neural activity. To establish a causal link between the effects of music on neural activity to improve memory function, future research needs to adopt a clear and consistent approach to measure brain activity during music engagement through neuroimaging techniques that can track the brain's real-time activity during music engagement.

Future MBIs studies should include a conceptual framework to guide the design of the intervention, a clear research hypothesis, a core set of data elements included in the study, a rich description of the intervention, a detailed protocol for implementing the intervention, and control groups (Edwards et al., 2023).

Adding to this, music's ability to activate emotional and cognitive systems through reward-related pathways should be further researched to improve MBIs potential to enhance memory recall (Ferreri et al., 2021; Sayal et al., 2024). A better understanding of how music listening can activate reward-related structures such as the amygdala and putamen (Sayal et al., 2024), and how dopamine modulation affects memory performance linked to musical pleasure (Ferreri et al., 2021) could lead to more personalized and targeted MBI protocols. Research on ADHD, for instance, demonstrates how music therapy can modulate individuals' serotonin (5-HT) and dopamine (DA) levels, potentially leading to improvements in emotion regulation and working memory (Park et al., 2023).

Koelsch (2009) also argues how music's ability to activate reward-related structures, indicates that the therapeutic benefits of MT may not only stem from its cognitive stimulation but also from the emotional salience that comes with listening to music. This theory about emotion and memory could explain why music may be effective in treating disorders that involve cognitive deficits or emotion dysregulation, such as AD and ADHD.

Furthermore, Individual differences in music-reward sensitivity should also be considered when developing novel MBIs to clarify how these differences modulate the impact of music on memory, and how emotional arousal during engagement with music may contribute to long-term memory improvements. By further exploring these neuroscientific aspects, research could explain how MBIs work at the brain level, leading to more targeted and effective interventions.

DISCUSSION AND CONCLUSIONS

This thesis has reviewed several studies and papers that explore music's effects on the brain in a neuroscientific context, and its implications for music-based interventions (MBIs), with the aim of providing a comprehensive framework for facilitating future developments of MBIs. We have looked at how music activates multiple brain systems such as auditory, motor, emotional, reward and memory systems, with some of them working simultaneously in response to music.

Research has suggested the reward system's importance for memory consolidation, particularly the role of dopaminergic pathways. Findings revealed how the amygdala and putamen, which are key structures in the reward system, play a crucial role in the emotional response to music. This emotional engagement, especially when perceived as pleasurable, is believed to activate dopaminergic activity, which can lead to enhanced memory encoding and consolidation. These findings support the idea that music can be used as a cognitive enhancer by stimulating reward pathways in the brain.

Moreover, a recent study demonstrated how individual differences in music reward sensitivity can be linked to white matter microstructure in pathways connecting auditory and reward related regions. Particularly, reduced connectivity between the STG, OFC, and NAcc was linked to lower sensitivity to musical pleasure. These findings are of high importance for the development of future MBIs, which may need to consider individual differences in neural connectivity to maximize their beneficial effects on cognition.

Although findings from recent studies contribute to the neuroscientific understanding of how music activates and impacts the brain, several limitations remain in this field of research. A major concern is the lack of data from methodologically rigorous, well-powered studies that can validate the observed effects of MBIs on memory and cognition. Many existing studies lack standardized protocols, making it difficult to compare results across diverse populations and conditions. Additionally, many studies in this field have not been designed within a scientific and theoretical framework, which weakens the interpretability and generalizability of their findings. Given the findings that music can activate memory, motor, and emotional systems, MBIs may offer promising support for individuals with neurodegenerative disorders such as Alzheimer's disease (AD) and Parkinson's disease (PD). Recent findings also indicate the potential of MBIs to support emotion regulation and executive functioning in ADHD populations. By engaging reward pathways and elevating motivation in ADHD individuals, music therapy may help sustain attention and improve working memory in ways that traditional pharmacological therapies may not. To further maximize the benefits of MBIs, I believe they need to be tailored to the target population receiving the intervention, while also considering individual differences in neural structures. MBIs for AD should focus on improving memory and emotional connection, while MBIs for PD should put an emphasis on improving motor coordination and rhythmic movement, and MBIs for ADHD should aim to support emotion and attention regulation, impulse control and working memory. To ensure that MBIs align with the specific needs of each target population, findings from the reviewed literature should be both integrated and further explored in the development of novel intervention protocols.

In conclusion, I believe that the existing neuroscientific research on music and the brain provide an important foundation for the development of novel, more targeted and effective MBIs. Music therapy shows promising outcomes for clinical populations, particularly in improving cognitive functions such as memory, emotion regulation and motor control. By further exploring the neural mechanisms involved in music perception, reward, and memory, I believe its therapeutic potential could be significantly improved. By addressing current methodological limitations, future studies can help strengthen the scientific basis of MBIs and support their application in therapeutic settings for clinical populations.

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