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The transformative power of music: Insights into neuroplasticity, health, and disease

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ABSTRACT

Music is a universal language that can elicit profound emotional and cognitive responses. In this literature review, we explore the intricate relationship between music and the brain, from how it is decoded by the nervous system to its therapeutic potential in various disorders. Music engages a diverse network of brain regions and circuits, including sensory-motor processing, cognitive, memory, and emotional components. Music-induced brain network oscillations occur in specific frequency bands, and listening to one's preferred music can grant easier access to these brain functions. Moreover, music training can bring about structural and functional changes in the brain, and studies have shown its positive effects on social bonding, cognitive abilities, and language processing. We also discuss how music therapy can be used to retrain impaired brain circuits in different disorders. Understanding how music affects the brain can open up new avenues for music-based interventions in healthcare, education, and wellbeing.

1. Introduction

Music is an essential part of human life. Many of us have experienced excitement and emotions induced by chords, rhythms, and melodies. Long before music had been demonstrated to be a valuable tool for gaining an insight into various brain functions, the ancient Greeks already knew about the importance of this art. Plato characterized music as a guide toward goodness as it could touch the soul (Schoen-Nazzaro, 1978).

The process of deciphering sound involves several brain areas working in concert to grant the perception of a sound along with the emotional valence for a specific melody. The music perception occurs through a series of events, starting with sound waves transforming into an electric signal, which then progress through the auditory nerve to the brainstem and activates cortical areas, allowing the perception of a specific sound (Koelsch and Siebel, 2005; Moreno and Bidelman, 2014). This intricate process not only contributes to our auditory experience but also plays a crucial role in the potential mental health benefits associated with music.

Besides passive music listening, music involves playing and creating, turning it into a unique experience (R. Zatorre, 2005). The acquisition of musical skills through repetitive training causes structural adaptations in the brain. Proprioception and auditory feedbacks are crucial while one learns to play an instrument, and long-term practice results in fewer neurons being recruited to execute the same movements (Gaser & Schlaug, 2003; James et al., 2014; Krings et al., 2000). Engaging in the creative process of music production not only enhances musical skills but also fosters cognitive and motor skill development, contributing to overall mental well-being.

Benefits of musical experiences begin already during pregnancy. Engaging with music by either performing it or simply listening to it improves the mood and well-being during pregnancy, and strengthens the bond between a mother and her infant (Corbijn van Willenswaard et al., 2017; García González et al., 2018; Hepp et al., 2018; Wulff et al., 2021). Early music experiences can improve the development of cognitive, emotional, physical, and social domains (M. S. Barrett et al., 2019; Cassidy et al., 2020; Ding et al., 2019; Fujioka et al., 2006; Sutcliffe et al., 2020; Swaminathan and Schellenberg, 2020). Among older adults, musical experiences contribute to their well-being, and are also associated with sustained brain volume and activation of networks involved in executive functions, memory, language processing and emotions (Bugos et al., 2007; Chaddock-Heyman et al., 2021; Seinfeld et al., 2013). These positive effects on well-being highlight the crucial role of music in promoting mental health across the lifespan.

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Music benefit individuals both in health and disease. Several studies show that many painful conditions and disorders can be alleviated by music (Düzgün and Karadakovan, 2021; Feneberg et al., 2021; Gauba et al., 2021; Kim and Jeong, 2021; Monsalve-Duarte et al., 2021; C. Wang and Tian, 2021). When a painful stimulus is applied to volunteers under control conditions while listening to their favorite songs, they report lower pain rating scores as music modulates pain responses in cortical regions, brainstem and spinal cord (Dobek et al., 2014). This pain modulation highlights one of the proposed mechanisms by which music exerts its effects on mental health, acting as a distraction from pain and modulating neural responses in regions associated with pain perception.

In addition, in a spontaneous and effortless way, music can trigger memories, awake emotions and intensify social bonding (Molnar-Szakacs and Overy, 2006). Improved attention and communication were observed in children with severe neurological impairments (Bringas et al., 2015) and a task-dependent cortical reorganization in stroke patients occurs after piano and electronic drum pad lessons (Amengual et al., 2013). Music interventions are also promising therapies for mood, vigilance and the overall quality of life in patients with Parkinson's disease (Park and Kim, 2021; Pohl et al., 2020), Alzheimer disease and other nervous system injuries (Gómez Gallego and Gómez García, 2017; Martínez-Molina et al., 2021; Paprad et al., 2021; Pezzin et al., 2018).

The primary goal of this literature review is to provide an insight into how music is decoded by the nervous system and its impacts on brain function, as well as how it can unlock various brain states, engage different brain circuits, and induce the release of neuromodulators. We argue that given the fact that music imposes unique demands on the nervous system, by discussing differences between musicians' and non-musicians' neuronal network, we can better understand how music is being utilized to retrain impaired brain circuits via music therapies for different disorders.

2. The neural basis of the brain-music interaction ('Brain on music')

2.1. *Neurophysiology of the perceptual processing of music (passive involvement)*

Music, as any auditory stimulus, is transmitted by a vibration of air, which is then transduced into electrical impulses by the cochlea. The cochlea is a spiral-shaped cavity in the inner ear that permits for diverse frequencies to activate dedicated regions along the spiral (known as a tonotopic map). From the cochlea, sound waves-induced nerve impulses are carried to the brain for interpretation (Casale et al., 2021). A broad spectrum of sound features (e.g., pitch, timbre, sound intensity, interaural disparities) are encoded by diverse neural response properties and transformed to the auditory brainstem, namely superior olivary complex and inferior colliculus (Langner and Ochse, 2006). From these brainstem regions, topographically organized auditory information travels to the auditory thalamus, specifically through the ventral geniculate body to the primary auditory cortex (A1) (Smith et al., 2012; Winer et al., 2002). This pathway is known as the lemniscal pathway, and it represents the major auditory signal processing pathway. The A1 receives diverse temporal rate representations of acoustic signaling and uses them to encode for slowly changing sounds, and a neural firing rate-based representation to encode for fast varying sounds (X. Wang et al., 2008). The internal representations of sound characteristics in the A1 no longer reflect the original acoustic architecture. Sound structure alterations are imperative for the A1 to achieve sound segmentation, syntax processing, and multisensorial integration (X. Wang et al., 2008).

Since music is a multisensory stimulus, music listening activates A1 along with motor and pre-motor regions, such as basal ganglia, primary motor areas, supplementary motor areas, and cerebellum (Pando-Naude et al., 2021). The A1 connectivity with the fronto-temporal-cerebellar circuit yields perceptual processing during music listening (Chen et al., 2008). Whereas A1 co-activation with motor, pre-motor, insula, and cerebellum is related to the processing of emotional content of music (Pando-Naude et al., 2021). Another important functional loop between A1 and inferior frontal regions (particularly in the right hemisphere) allows integration of working memory related to temporal dynamics of the sound. Since auditory events are not static, the brain's ability to concatenate precise auditory information is crucial for the ability to maintain dynamic information for further processing (R. J. Zatorre and Salimpoor, 2013). Passive engagement with previously unheard music activates subcallosal cingulate gyrus, prefrontal anterior cingulate and retrosplenial cortices, hippocampus, anterior insula, and ventral striatum (S. Brown et al., 2004).

One of the most notable features of music is pitch. Lateral cortical regions to A1 are associated with pitch processing (Johnsrude et al., 2000; McDermott and Oxenham, 2008). Studies using functional magnetic resonance imaging (fMRI) scan indicate that pitch processing occurs in a hierarchical manner, where more abstract sound properties are encoded as one proceeds along with the sound analysis streams (R. J. Zatorre et al., 2007). Pitches unfold over time and are perceived as a melody. This dynamic perceptual process engages anterior and posterior auditory pathways (Patterson et al., 2002).

Along with the pitch, music perception relies on the rhythm. Anatomically, pitch and rhythm perception is separable as individuals with brain injuries in a particular area can still perceive either pitch or melody (depending on the area), but not both (Peretz and Coltheart, 2003). In neuroimaging studies where subjects are listening only to rhythms, the cerebellum, the basal ganglia, premotor cortex, and supplementary motor area are activated (Grahn and Brett, 2007; Sakai et al., 1999).

2.2. *Music performance: auditory-motor interaction (active involvement)*

In contrary to passive music listening, music performance requires high precision control over motor execution and auditory perception systems. Meticulous motor control is required for the timing, sequence, and spatial organization of the movement. These motor control components are associated with the architecture of musical rhythm, and the tactile component of playing a musical instrument. The ability to execute the movement at the precise timing has been linked to a neural counter mechanism, which infers time through neuronal oscillations (Spencer et al., 2003; Wing, 2002), or a kinematic property of movement on its own (Penhune et al., 1998). The premotor and motor cortices, cerebellum, and the basal ganglia contribute to the motor processes (timing, sequence) related to music performance (R. J. Zatorre et al., 2007). Activation of the supramarginal gyrus has been associated with tactile processes and limb positioning (Pando-Naude et al., 2021).

An auditory-motor interaction, which occurs when actively engaging with music production can be defined as feedforward and feedback communication. The motor system controls the fine movements when playing an instrument. The produced sound is then processed by auditory circuits and adjust the motor output, if needed (R. J. Zatorre et al., 2007). The acquisition of auditory-motor sequences relies on cingulate and cerebellar beta oscillations, which reflect the processing of auditory feedback-related adjustments during sensorimotor learning and performance (Herrojo Ruiz et al., 2017). Brain regions related to motor planning and execution are co-activated (e.g., precentral, middle frontal and supramarginal gyri). Along with motor function related to instrument playing, these brain regions are also recruited during sensory-motor coupling (Hanakawa et al., 2008).

The emotional content during an instrument playing must be passed onto the listener. The anterior cingulate gyrus and insula are involved in emotional information analysis and perceptual processing. The top-down processing and control of emotional meaning, and bottom-up analysis of the emotional content occurs in the anterior cingulate gyrus solely (Pando-Naude et al., 2021). Interestingly, when professional composers are engaged with music creation, the integration of the primary visual and motor areas is not required. These brain regions are instead involved in functional connectivity between the anterior cingulate cortex (ACC) and the default mode network (DMN) to integrate sound with its emotional content (Lu et al., 2015).

2.3. Neural circuits and neuromodulatory systems involved in the musical experience

Music can evoke a variety of emotions, feeling of pleasure/euphoria, increase in motivation and arousal. Music's ability to tap into diverse psychological and physiological brain states is mediated by the activation of the diverse neural circuits and neuromodulatory systems. In clinical settings, music acts as a non-pharmacological intervention that can attenuate various diseases, thus the mechanisms by which music exerts therapeutical effects are of great interest.

Listening to music, especially to subjectively preferred songs, engages brain pleasure pathways. A study using positron emission tomography (PET) measured regional cerebral blood flow changes in response to the subject's chosen highly pleasurable music, which would evoke the experience of "chills" or "musical frisson" (Blood and Zatorre, 2001). With increasing intensity of music-evoked pleasure, cerebral blood flow changes were registered in brain regions associated with reward, motivation, arousal, and emotions, namely ventral striatum, midbrain, amygdala, orbitofrontal, and ventral medial prefrontal cortices (Blood and Zatorre, 2001). These brain regions are similarly activated by highly rewarding stimuli such as food, drugs of abuse, sex (Berridge and Kringelbach, 2008; Oei et al., 2012). Although music does not represent any biologically significant stimulus, it recruits the same brain circuits as the ones that are involved in pleasure and seeking reward. Reward processes are known to recruit dopamine and opioid systems, as illustrated in studies in animal models (Peciña and Berridge, 2013) and humans (Nummenmaa et al., 2018; Oei et al., 2012). The dopaminergic system related to reward mechanisms signals through the mesocorticolimbic pathway, which is comprised of the ventral tegmental area (VTA) (one of the two main nuclei of dopamine neurons in the brain) projecting to the ventral striatum, specifically nucleus accumbens (NAc) (Lammel et al., 2008). The dopamine release in response to highly pleasurable music was measured by ligand-based PET scanning. The study registered a release of dopamine in the dorsal and ventral striatum (NAc and the caudate putamen) at the peak of emotional arousal when listening to one's preferred song (Salimpoor et al., 2011). Furthermore, a causal link between dopamine release and mediation of musical reward experience was shown in a study using pharmacology. The study participants received (through oral administration) either dopamine precursor (levodopa), D2-like dopamine receptors inhibitors (risperidone), or placebo (lactose) while listening to music. The results revealed that dopamine receptor inhibition impaired participants' ability to experience pleasure when listening to music, whereas dopamine precursor enhanced musical pleasure (Ferreri et al., 2019).

In animal models, reward associated with hedonic experiences in the NAc is typically mediated by opioids, in contrast to dopamine transmission shown in human studies exploring the music-associated feeling of pleasure (Berridge and Kringelbach, 2008). According to animal studies, music-evoked pleasure is not solely mediated by dopamine but there is also a contribution of opioid signaling. This hypothesis has been tested in a study in humans using naltrexone (NTX), a μ-opioid antagonist, in a double-blind crossover study. Participants were administered either NTX or a placebo and subjected to listen to pleasurable music recordings of their choice, which would reliably produce intensely pleasurable feelings. NTX administration decreased the physiological reactions associated with positive emotional experiences and self-reported measures of real-time pleasure (Mallik et al., 2017). A similar study using NTX and placebo (d3 vitamin) found the opposite results. The μ-opioid antagonism did not change self-reported pleasure, and it only dampened pupil response and decreased arousal during peak pleasure when listening to music (Laeng et al., 2021). These experiments suggest that the opioid system is not the primary mediator of music-evoked pleasure and feeling of reward. However, music's ability to stimulate opioid release is a powerful tool for pain-related therapeutic conditions, thus further experiments on opioid system recruitment by music are needed.

Along with the subjective increase of psychological wellbeing, music exerts various physiological effects on the human body, mediated via the autonomic nervous system (ANS). Music can induce changes in heart rate, respiratory rate, blood pressure, electrodermal skin conductivity, muscle tension, peripheral temperature (Blood and Zatorre, 2001; Ferreri et al., 2019; Salimpoor et al., 2011). Chills evoked by highly pleasurable music are physiological markers of intense ANS activation (Mori and Iwanaga, 2017). The ANS function is primarily mediated by neuromodulators noradrenaline, adrenaline, and acetylcholine (McCorry, 2007).

In the brain, the primary source of noradrenaline (NA) is the locus coeruleus (LC), which activity has been associated with pupil dilation (Murphy et al., 2014), heart-rate variability (Mather et al., 2017), emotional reactivity (Lerner et al., 2009). Pupil dilation increases in response to liked, predictable melodies (Bianco et al., 2019). Music-induced chills are correlated with greater pupil dilation, implicating the central NA system in this phenomenon (Laeng et al., 2016).

Another neuromodulator affected by auditory stimulation by music is serotonin (5-HT). Ascending from its source brainstem nucleus Dorsal Raphe, serotonin neurons project to parts of the auditory system where this monoamine neuromodulator acts as a prominent mechanism linking external auditory processing with the internal state (Hurley and Hall, 2011). Serotonin signaling has been mostly implicated in music perception. In adult rats, exposure to classical music (Mozart's sonata) was associated with an increase of serotonin metabolites concentration in caudate-putamen (CPu) (Moraes et al., 2018). Music's effect on serotonin release in humans was studied by using the platelet model of serotonin content. According to the model, serotonin platelet content reflects the serotonin content in neurons, such that decreased values for the intracellular content reflect higher serotonin transmission history (Evers and Suhr, 2000). In response to a pleasant music, the researchers measured an increase in serotonin platelets. In contrast, listening to unpleasant music correlated with a decrease in serotonin platelets, indicating an increased release of serotonin upon unpleasant music. The results of the study suggest that serotonin release is modulated by the music of different valence (Evers and Suhr, 2000). Serotonin's role on music listening was further investigated in a study where participants took lysergic acid diethylamide (LSD) (a psychedelic drug acting as 5-HT_{2A} receptor agonists) or LSD + ketanserin (5-HT_{2A} receptor antagonist) and their brain activity was assessed by collecting blood oxygen level-dependent (BOLD) signal during music listening. The results show that serotonin receptor 5-HT_{2A} signaling is implicated in neural response to music in brain regions related to higher-level musical processing, and supporting music-induced emotionality, meaningfulness, and connectedness (F. S. Barrett et al., 2018). Although evidence on serotonin modulation by listening to music is sparse, the comprehension about neuromodulatory underpinnings of musical experience is crucial for health-relevant implications in daily life and therapeutical settings.

Additionally, some neuropeptides, for example, oxytocin (Hansen and Keller, 2021; Keeler et al., 2015), are subjects to the modulation by musical experience. The relation between oxytocin and music will be discussed in the context of social bonding (part 3).

2.4. Music-induced brain network oscillations

Music engages an intricate set of brain regions and functional circuits, such as sensory-motor processing, cognitive, memory, and emotional components (Blood et al., 1999; Blood and Zatorre, 2001; Menon and Levitin, 2005). Moreover, music can modulate diverse brain circuits and induce a release of various neuromodulators (Evers and

Suhr, 2000; Ferreri et al., 2019; Moraes et al., 2018). Due to aforementioned reasons, music represents an ideal tool to investigate multi-modal brain functioning and the integration of multisensory information.

Brain circuits recruited when listening to/playing music translate into large-scale brain oscillations that can largely impact neural population rhythms and thus, the general brain states. Neural population rhythms are cyclic changes in baseline neuronal activity that can be observed in the local field potential (LFP), the electroencephalogram (EEG), and the magnetoencephalogram (MEG) (Slézia et al., 2011). These neuronal population rhythms are usually evident in neocortical and thalamic brain regions (Buzsáki and Draguhn, 2004; Slézia et al., 2011). Thalamocortical oscillations occur in specific frequency bands of delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (30–70 Hz) (Buzsaki, 2006). Neural oscillations are the means of communications between different nodes of the brain regions underlying cognitive processes or brain states (Buzsáki and Draguhn, 2004).

Connectivity dynamics of the neural circuits related to pleasantness evoked by unfamiliar and familiar music has been addressed in a study using EEG. The authors observed an increase in right frontotemporal theta synchronization along with higher reported pleasantness evoked by previously unheard music. Significant theta synchronization occurred between right temporal and left parietal signals (Ara and Marco-Pallarés, 2021). Instead, inter-hemispheric temporoparietal theta synchronization has been linked to pleasant feelings evoked by familiar music. Together these results suggest that diverse theta connectivity patterns reflect the value assignment to music depending on whether the music is familiar to the listener or not (Ara and Marco-Pallarés, 2021). Theta and alpha frequency bands are observed when processing the music stimuli of different valence (consonant and dissonant chords). The oscillation of these frequencies is driven by the amygdala and engages the orbitofrontal and the auditory cortices (Omigie et al., 2015).

Music listening evokes cortical activity in the high-gamma band in the cortical regions ranging from the temporal lobe to the inferior frontal gyrus. Reversed temporal flow is observed during music recall. These mechanisms demonstrate bottom-up and top-down processes when listening to music and during the recall of a musical fragment (Ding et al., 2019). Beta oscillations play a significant role in temporal predictions to complex rhythms when listening to music, and enhance the processing of musical content (Doelling and Poeppel, 2015). Musical improvisation and music creation is linked to feelings of ‘flow’ arising from a weak activity of the executive control network. The connectivity of sensorimotor and executive control networks does not differ when imagining the performance or performing (Vergara et al., 2021).

Large-scale brain synchronization differs in musicians and non-musicians. When listening to emotional sounds, musicians show greater activity in frontal theta and alpha bands (Nolden et al., 2017). Professional musicians also exhibit more intense patterns of emotional activation and related brain synchronization when they listen to music (Mikutta et al., 2014). In a study using EEG, mid-frontal theta and posterior alpha-band activities during music perception were observed along with professional musicians’ more consistent ratings (compared to non-musicians) of subjective arousal in response to classical music (Mikutta et al., 2014).

The brain state associated with music listening is the DMN. The DMN is related to specific brain functions, such as self-referential views, empathy, self-awareness, mind-wandering, imagining the future (Broyd et al., 2009; Gusnard et al., 2001). This network is active when people listen to liked music, suggesting compatibility with the listener’s reported experiences of music-evoked introspection, mind-wandering, and self-referential thoughts (Wilkins et al., 2014). The activation of the DMN is related to the generation of innovative ideas, creation and inventiveness (Heuvel et al., 2009; Immordino-Yang et al., 2012). Thus, listening to one’s preferred music might grant the easier access to these brain functions. This could have important therapeutical implications, where music could improve executive functions and emotional states, act as an anxiolytic (Thaut et al., 2008). Listening to sad music, compared with happy music, is associated with stronger mind-wandering and greater transitions to the DMN (Taruffi et al., 2017). These results suggest that the emotional valence of the music can modulate the engagement of the DMN activity (Taruffi et al., 2017).

3. Insights into brain function through musical experience

3.1. Music and neuroplasticity

Neuroplasticity is brain’s ability to undertake functional and structural modifications in response to experience or injury (von Bernhardi et al., 2017). These alterations might start as cellular changes and progress to macro-modifications of the brain. Neuroplasticity can manifest as changes in neuron’s morphology, modifications of synaptic weight, synaptic pruning, cortical remapping (Olszewska et al., 2021; Stegemöller, 2014; R. J. Zatorre, 2013). Music, as a multisensory stimulus, has been shown to induce structural and functional changes in the brain, mostly due to continuous engagement of the brain regions related to music listening and/or performance.

Several studies have investigated the changes in musicians’ brains as a result of years of musical practice. The corpus callosum, a fiber tract connecting the two cerebral hemispheres, is substantially larger in musicians than in non-musicians, and the size of the corpus callosum positively correlated with the years of musical training (Reybrouck and Brattico, 2015). In multiple studies, it was confirmed that the corpus collosum exhibit a larger volume in musicians who started their practice before the age of seven, as opposed to musicians who had a later onset (Reybrouck and Brattico, 2015; Schlaug et al., 2009; Wan & Schlaug, 2010).

Notable music-induced changes in white and grain matter were also reported. Bengtsson and colleagues (Bengtsson et al., 2005) studied the effects of long-term piano playing on the white matter in childhood, adolescence, and adulthood using diffusion tensor imaging. They discovered that pianists have more structured right posterior internal capsule, than non-musicians. Training can cause plastic changes in the white brain matter if training occurs during periods of fibre tracts maturation. Another study scientist looked at both grey and white matter in pianists and non-musicians (Han et al., 2009). In pianists, compared to non-musicians, grey matter density was higher in the left primary sensory-motor cortex and right cerebellum. Additionally, white matter integrity was also higher in the right posterior internal capsule. These findings suggest that long-term piano practice may cause grey and white matter adaptations in motor brain regions, which could affect the number of synapses, glia volume, myelination, and axon diameter (Han et al., 2009).

As an evidence of music-related cortical remapping, Elbert and colleagues (Elbert et al., 1995) found that string players have the cerebral representation augmented to the fingers of the hand that are used mostly for playing the instrument. The more a given finger is used for playing an instrument, the larger the increase in cortical response is. Cortical auditory representation in musicians is stronger compared to non-musicians as the magnitude of cortical activation for piano tones is by 25% greater in musicians. Both studies revealed a greater increase of cortical representation in musicians who began musical training at young age (Elbert et al., 1995; Pantev et al., 1998).

As previously established by numerous studies, instrument playing engages the motor cortex and other structures involved in motor movement coordination and initiation. Motor movements can be as simple as moving the musicians’ fingers, or as complex as coordination of foot movement with hand movement. Music playing increases the size of grey matter in the primary motor cortex. The size of the right and left motor cortex in musicians and non-musicians was evaluated (Amunts et al., 1997). Both groups had leftward asymmetry but musicians had a smaller degree of asymmetry due to larger right motor cortex. The researchers also discovered a negative relationship between the size of the motor cortex in both hemispheres and the age at which musical practice began (Amunts et al., 1997). The structural alterations in the motor cortex were a result of intensive and early hand skill instruction. Other structures seen to be altered by music expertise are the cerebellum (Olszewska et al., 2021; Reybrouck and Brattico, 2015) and precentral gyrus, an area known for hand/finger movement integration (Wan & Schlaug, 2010). Schlaug group (Schlaug et al., 1995) measured the volume of the cerebellum in musicians and non-musicians. They found that male musicians had a higher average cerebellar volume than non-musicians. These results showed that the cerebellum undergoes microstructural adaptations in response to early initiation and continued practice of complex finger sequences.

The auditory cortex is highly plastic in response to music as a year of music training can cause structural changes in the primary auditory areas (Kraus and Chandrasekaran, 2010). Studies using diffusion tensor imaging have also shown that music exposure leads to stronger connection between the superior and middle parts of the gyrus (Meyer et al., 2012). Studies using fMRI scans have shown that all regions of the Heschl's gyrus are activated stronger when exposed to music related tasks involving rhythm and melody (Wan & Schlaug, 2010). The planum temporal, a brain structure crucial in processing functions that allow for the processing of music and speech, has been characterized by leftward asymmetry and a greater size in musicians due to their ability to perceive and process absolute pitch (Meyer et al., 2012; Reybrouck and Brattico, 2015; Wan & Schlaug, 2010). Using voxel-based morphometry analysis, Gaser & Schlaug (2003) discovered higher grey matter volume in the motor, auditory, and visuospatial cerebral areas in musicians. The findings point to structural brain adaptations in response to skill acquisition and their long-term repetition.

The hippocampus has also been found to have a greater grey matter volume in professional musicians in comparison to non-musicians (62). Various studies were curious about the effect of musical process on the connectivity between the NAc and other regions of the brain. The findings showed that different sides of the NAc are connected with different parts of the brain depending on whether the individual is a musician or not. For instance, the NAc functional connectivity with the hippocampus is stronger in non-musicians as opposed to the preferentially stronger connectivity within the temporal pole and ventromedial frontal areas in musicians (Reybrouck and Brattico, 2015).

Musician's engagement with music instruments is related to an improvement of various music-related abilities. For instance, musicians are better at pre-attentively extracting information out of musically relevant stimuli, and demonstrate superior temporal integration (Koelsch et al., 1999; Rüsseler et al., 2001). Another study demonstrated that a year of high-intensity aural skills training in musicians improved neural responses to temporal novelty in the hippocampus. This improved sensitivity in the hippocampus positively correlated with musical abilities of the participants (Li et al., 2018). Musacchia and colleagues (Musacchia et al., 2007) demonstrated that changes in functional organization also occurs within subcortical sensory structures in musicians compared to controls. Specifically, musicians have earlier and larger auditory and audiovisual brainstem responses to speech and music stimuli. The magnitude of the brainstem response to speech stimuli positively correlated with the years of engagement in musical practice, suggesting that musical training enhances the representation of the pitch in the brain. Even though there are exceptional cases where musicians created beautiful pieces while deaf, like Beethoven, the majority of musicians rely heavily on their auditory perception to create music as well as to perform it. Musicians are better at detecting and processing micro-changes in essential aspects of music such as pitch, timbre, and tempo (Kraus and Chandrasekaran, 2010; Meyer et al., 2012). Children also showed higher sensitivity to pitch patterns that are of their mother tongue (Kraus and Chandrasekaran, 2010). These advantages are due to more precise neuronal representations in their auditory cortex (Meyer et al., 2012). Individuals who were involved in music whether on long-term or short-term basis have shown improved verbal memory (Kraus and Chandrasekaran, 2010; Wan & Schlaug, 2010), faster neural response to speech (White-Schwoch et al., 2013), and perform better in auditory tasks (Meyer et al., 2012) due to their enhanced auditory attention (Kraus and Chandrasekaran, 2010). In the elderly individuals, volume and activity decrease in brain regions is a typical sign of aging. When compared to non-musicians, practicing musicians have more grey matter volume in the left inferior frontal gyrus. In contrast to non-musicians, musicians did not show substantial age-related decline in overall brain volume or in brain areas such as the dorsolateral prefrontal cortex and the left inferior frontal gyrus. As a result of their regular musical practices, musicians tend to be less sensitive to age-related degenerations in the brain (Wan & Schlaug, 2010). Over 75-year-old participants were monitored for five years. When compared to those who infrequently played a musical instrument, those who regularly played a musical instrument were less likely to be diagnosed for dementia. Playing music had a larger protective impact than other cognitive tasks like reading, writing, or performing crossword puzzles (Wan & Schlaug, 2010).

3.2. *Memory, emotions, and cognitive domains*

As a research on music increases, researchers are drawn to explore the effects of music on memory, emotions, and cognitive domains. A study by Ferreri and Rodriguez-Fornells (Ferreri and Rodriguez-Fornells, 2017) explored the effect of music-induced reward on episodic memory, revealing a correlation between pleasurable music, dopamine release, and enhanced memory (Ferreri and Rodriguez-Fornells, 2017). Brain activation during music listening or recall involves regions such as the temporal and frontal lobes, with anatomical differences observed in experienced musicians (Ding et al., 2019; Ford et al., 2011; Groussard et al., 2010). Musicians, particularly, exhibit denser grey matter in the left hippocampus, resulting in more vivid and intense music-associated memories (Groussard et al., 2010). Verbal memory advantages in musicians, proven by studies (Franklin et al., 2008; Thaut et al., 2005), can be compromised by articulatory suppression, indicating enhanced verbal memory rehearsal mechanisms (Franklin et al., 2008). Additionally, exposure to classical music during study and sleep enhances short-term memory, especially in females (Gao et al., 2020).

The retrieval of memories through music can evoke emotions akin to those experienced during the initial events. Music-evoked emotions, conveyed as effectively as verbal language (Proverbio and Russo, 2021), induce powerful feelings, including chills or tears (Lundqvist et al., 2009; Mori and Iwanaga, 2017). Chills and tears represent happy or sad emotions, respectively, with tears having a cathartic effect (Mori and Iwanaga, 2017). Happy music induces more happiness, while sad music increases empathy and pain processing (Lundqvist et al., 2009; Cheng et al., 2017). The limbic system, especially the amygdala, plays a crucial role in music-evoked emotions (Koelsch et al., 2021). Furthermore, music can influence visual information, affecting visual alertness and attention shifts (Koelsch, 2014).

Music perception, composition, and imagery constitute basic contemporary music procedures engaging auditory cortices, sensorimotor cortices, and the cerebellum. Imagery, particularly auditory imagination, enhances pitch accuracy, while motor imagination aids coordination in large groups (Keller, 2012; R. Brown and Palmer, 2013; Pando-Naude et al., 2021). Directed imagination exercises with music influence vividness, sentiment, and perception, showcasing music's potential in therapeutic tools like Exposure Therapy and Imagery Rescripting (Herff et al., 2021). This suggests that music could be integrated into the standard therapeutic protocols, potentially enhancing the effectiveness of these treatments and improving patient outcomes. Imagination is a powerful skill used by athletes and musicians to enhance their performance, impacting various cognitive and emotional aspects (Keller, 2012; Pando-Naude et al., 2021).

Multiple studies establish a positive correlation between music playing and cognitive abilities (Grassi et al., 2017; Hars et al., 2014; Okada and Slevc, 2018; Schneider et al., 2019). Musical experience influences working memory processes (Okada and Slevc, 2018), and elder musicians exhibit enhanced working memory and visual spatial performance (Grassi et al., 2017). Weekly music-based multitask training reduces anxiety in older adults (Hars et al., 2014), and long-term music training improves both auditory and visual working memory in non-professional musicians (George and Coch, 2011; Putkinen et al., 2021). Music practice enhances attention, working memory, and speech-in-noise perception, indicating improved cognitive factors (Kraus et al., 2012). This leads to musical training allowing one to hear speech in noise, due to the enhanced cognitive factors (Kraus et al., 2012). Another study found a significant increase in verbal intelligence among children in a music group that trained their music listening skills (Moreno et al., 2011). During an executive-function task, verbal intelligence improvements were linked to functional brain plasticity changes (Moreno et al., 2011). The children also had better vocabulary knowledge, indicating an increase in verbal intelligence after music training exposure (Moreno et al., 2011). Thus, the effects of music training on language and executive functions are related (Moreno et al., 2011). Interestingly, music, unlike other art forms, can affect brain processes concerning auditory and other mechanisms (Moreno and Farzan, 2015). Research has shown that children who had music training achieved better results on second language acquisition and musical achievement, on the contrary to children who did not have any musical training (Yang et al., 2014; Putkinen et al., 2021). However, development of cognitive abilities, such as mathematical skills, did not improve in the musician group (Yang et al., 2014). A sample of undergraduates showed positive relationships between musical capability and duration of music training, socioeconomic status, short-term memory, general cognitive skills, and openness to new experiences (Swaminathan and Schellenberg, 2018). In the combined analysis of these factors, musical competence was associated with longer music training, better general cognitive skills, and more openness (Swaminathan and Schellenberg, 2018). Moderation analyses showed that participants who scored below the mean on the set measure of general cognitive skills showed the partial association between musical proficiency and music training (Swaminathan and Schellenberg, 2018). Furthermore, general cognitive skills and openness were indirectly associated with musical capability since they predicted music training, which was in turn related to musical competence (Swaminathan and Schellenberg, 2018). There are many factors that contribute to musical competence, including but not exclusive to music training (Swaminathan and Schellenberg, 2018). Researcher looked at the N400 effect while examining arousal levels of participants during reading comprehension with and without the music in the background. The N400 effect was smaller in the group that was reading without music, compared to the participants who were listening to background music, suggesting that background music increases the difficulty of semantic integration that occurs during reading comprehension (Du et al., 2020). Experimental evidence shows that music reduces cognitive dissonances, a discomfort caused by holding conflicting ideas simultaneously and inevitably leads to devaluation of conflicting ideas (Masataka and Perlovsky, 2012). Meditation involving singing or music listening has shown significant enhancement of subjective memory function and objective cognitive function (Innes et al., 2017). Additionally, research indicates that both verbal and auditory working memory rely on the ability to produce the instantly remembered sounds, which suggests that sensorimotor representations are vital for the temporary storage of auditory information in working memory (Schulze and Koelsch, 2012). Music training results in significantly higher visual spatial ability, executive functioning, and naming skills compared to those who do not practice music in any way (Strong and Mast, 2019). However, differences are not significant among those same groups regarding processing speed or episodic memory (Strong and Mast, 2019).

3.3. Social bonding

The attachment of memories to music does not only explain its association with emotions, but it is also a reflection on music's inherent social nature (Koelsch, 2014; Nummenmaa et al., 2021). In fact, the neural pathways activated by music processing are very close to those of social processing (Nummenmaa et al., 2021). Thus, music can allow for the attainment of social human needs (Koelsch, 2014). When groups of people come together to sing or play instruments, stress and arousal levels are reduced due to an increase in adrenocorticotrophic hormone levels after singing together (Keeler et al., 2015). Also, an increase in positivity, engagement, connectivity, and endorphin levels occurred (Weinstein et al., 2016), all while negative emotions decreased and positive ones increased (Kreutz, 2014). Moreover, singing in large groups of unfamiliar people seems to have a more powerful effect when compared to smaller more familiar groups (Weinstein et al., 2016). All in all, individual wellbeing and bonding increased dramatically when placed in a musical group. All these positive effects could be due to the increase in the levels of endorphins (Launay et al., 2016; Tarr et al., 2014; Weinstein et al., 2016), oxytocin (Keeler et al., 2015; Kreutz, 2014; Launay et al., 2016) and other hormones or neuromodulators (Launay et al., 2016) when in musical groups. Synchronized human activities, like group singing, were found to release endorphins (Launay et al., 2016) and increase pain thresholds (Weinstein et al., 2016). Moreover, endorphins and the endogenous opioid system were found to assist in social bonding (Tarr et al., 2014). Meanwhile, oxytocin induces social bonding conditions like communication, cooperation, and eye contact (Keeler et al., 2015). In the context of diseases, these findings suggest that music-based interventions, particularly those involving group activities, have the potential to modulate hormonal and neuromodulator levels, providing a therapeutic avenue for conditions related to stress, emotional well-being, and social bonding (Launay et al., 2016; Tarr et al., 2014; Weinstein et al., 2016; Keeler et al., 2015; Kreutz, 2014). Dancing also seems to facilitate bonding and produce positive emotions (Nummenmaa et al., 2021), and a stronger bond can form when there are similar musical preferences with others (Stupacher et al., 2020). Finally, children with autism appeared to be able to communicate better after being placed in music group therapies, with improvements in many areas of their brain's connectivity (Sharda et al., 2018).

3.4. Music, speech and language

The separate concepts of music and language have existed for decades. However, it is becoming more apparent that both music listening/production and language share certain properties that make these two processes interconnected (Peretz et al., 2015). This anatomical and functional link occurs because both linguistic and musical syntax share common syntactic processes for different domain-specific syntactic representations, executed by the same brain regions (Patel, 2003).

For instance, one study showed that people who were trained in music showed better semantic processing than those who did not have music training (Yu et al., 2017). However, phonological processing was not affected regardless of whether the person had musical training or not (Yu et al., 2017). Furthermore, semantic language processing and musical melodic analysis showed correlation at both the regional and network levels, proving, that they are associated, and that there is a neural basis link between them (Yu et al., 2017). In a study that attempted to investigate the effects of music on word learning, musical stimuli, regardless of the degree of stimuli, were found to effectively ease learning words and long-term retention of the learned words. Music helped to encode the speech signal rather than recognition of the words (Ma et al., 2020). The study also showed that encoding was improved, particularly in terms of word association, but also possibly in terms of word segmentation. The current findings suggest that including musical elements into speech improves both word learning and long-term memory (Ma et al., 2020). This suggests that incorporating music into therapeutic approaches for diseases involving language and memory functions could potentially enhance word learning and retention, providing a novel avenue for intervention strategies (Ma et al., 2020).

When listening to music, the pars orbitalis, a brain area involved in improving the linguistic structure of spoken and sign language, showed activity related to focal activation (Levitin and Menon, 2003). Moreover, vocal or instrumental music was found to preferentially activate the superior temporal gyrus (STG), specifically bilaterally in the anterior planum polare (Whitehead and Armony, 2018). While on the other hand, speech or singing engaged a great part of the superior temporal sulcus, suggesting that both areas integrate (Whitehead and Armony, 2018). Several fronto-parietal areas, primarily the dorsolateral prefrontal cortex, the supramarginal/angular gyrus and the precuneus, are activated when listening to autobiographical music (familiar own and/or other) (Castro et al., 2020). Also, familiar own music (compositions) activated brain regions including the medial prefrontal cortex, visual imagery, and reward and emotion networks, whereas familiar other music (favorite) activated reward networks, such as ventral striatum (Castro et al., 2020). Accordingly, familiar music containing self-related references (compositions) was associated with an enhanced activation of the autobiographical network during subsequent familiar naming (in comparison to music that did not contain self-related references); the precuneus was strongly associated with such processing (Castro et al., 2020).

It is hypothesized that having a minor superiority in decoding speech sounds may have led to the dominant role of the left hemisphere in many sophisticated linguistic functions (R. J. Zatorre et al., 2002). As a result, the right hemisphere may have played a crucial role in aspects of musical perception, especially those related to tonal pitch, and may have been a result of, and a complement to, this specialization of language (R. J. Zatorre et al., 2002). Another hypothesis suggests that, syntax in language and music is governed by hierarchical organization, as fundamental features of hierarchical control in the brain include functional architecture of the frontal cortex, which maintains abstract representations in anterior parts of the brain and more concrete representations preferentially in posterior parts, dual control function (i. e. inhibition and selection) of the basal ganglia, and the influence of abstract temporally extended processes on concrete motor processes by means of cortico-basal-ganglia-thalamus circuits (Asano et al., 2021).

Evidence suggests that using neural networks to model cognitive tasks such as word learning could help provide a greater understanding of the neural dynamics underlying these tasks (Elmer and Jäncke, 2018). One study have shown that subjects with no special musical training who are naively presented with different musical excerpts associate the musical extracts with specific words similarly (Koelsch et al., 2004). Consequently, event-related potential (ERP) results, particularly the N400 priming effect, for the music indicated no differences in terms of latency, scalp distribution, neural site, or amplitude between the music and language (Koelsch et al., 2004). Concurrent music processing delayed N400 effects only when melodies are familiar, whereas double violations of familiar melodies produce a sub-additive N400 effect (Calma-Roddin and Drury, 2020). Additionally, both early negativity effects (right anterior negativities RAN effects), which are associated with musical syntax, as well as the music N400, were delayed in onset for familiar melodies, and double violation cases associated with unfamiliar melodies also caused RAN effects to be delayed (Calma-Roddin and Drury, 2020, p. 400). Together, these patterns demonstrate the existence of interference effects within these domains and add evidence regarding previously unreported types of interactions to the collection of findings important to determining if language and music share similar mechanisms (Calma-Roddin and Drury, 2020, p. 400).

Experimental evidence shows that tonal music induces highly structured mental representations of musical pitch in both musicians and non-musicians (Patel, 2003). Language experience may contribute to an automatic encoding of subcortical electrophysiological responses to english syllables in native speakers as compared to non-native non-musicians. In other words, encoding of these cues in native speakers is enhanced (Intartaglia et al., 2017). A distinct finding was that the neural responses to formant frequencies were the same for native speakers and non-native musicians, suggesting that music training could recouperate for the lack of language exposure by encoding crucial acoustic information (Intartaglia et al., 2017). The acquisition of language and music seems to increase acoustic sensitivity in a functionally relevant manner, such as phoneme discrimination (Intartaglia et al., 2017). In one study, increasing syntactic complexity and distracting melodies caused the interference of one-timbre melodies with sentence recall (Fiveash et al., 2018). By contrast, alternating instruments in three-timbre melodies diminished interference on long-distance syntactic structure building, probably because they interrupted auditory streaming (Fiveash et al., 2018). Additionally, in contrast to three-timbre melodies, the participants had an easier time distinguishing syntactically coherent one-timbre melodies (Fiveash et al., 2018). Thus, results indicate syntactic analysis and auditory streaming may interact to influence recall of sentences (Fiveash et al., 2018). The beta and gamma frequencies in EEG have been shown to have the greatest significance for determining mental activities. The results of an analysis of the energy distribution in EEG channels show a clear correlation between mental processes and the external world perception. Hence, language skills may be affected by music training (Besedová et al., 2019).

4. Discussion

Music is a complex stimulus that engages multiple brain regions and circuits, influencing various domains of human functioning. The ability of music to influence the brain is due to the brain's neuroplasticity, the ability of the brain to reorganize and adapt to new experiences. Studies have shown that musical training can bring about structural and functional changes in the brain, resulting in increased grey and white matter density, larger corpus callosum, and greater cortical remapping in areas related to music performance. Moreover, music can improve cognitive, emotional, physical, and social domains, making it a valuable tool for promoting health and wellbeing.

One of the most remarkable aspects of music is its ability to tap into different brain states, influencing diverse neural circuits and neuromodulatory systems. The emotional valence of music modulates the engagement of brain regions involved in self-referential views, empathy, self-awareness, mind-wandering, and imagining the future. The activation of the default mode network (DMN) by music listening is also linked to the social and emotional functions of the brain. Music can trigger the release of hormones such as endorphins and oxytocin, which promote social bonding and alleviate pain. Music is a non-pharmacological intervention that can be used to treat various diseases, including stroke, Parkinson's disease, and dementia. Music therapy involves the use of music to address physical, cognitive, and emotional needs of patients. Music therapy can improve motor control, speech, language, and memory in stroke and Parkinson's disease patients. In dementia patients, music can trigger memories and improve mood, socialization, and quality of life. Music therapy can also reduce anxiety, depression, and pain in cancer patients.

The integration of music as a therapeutic tool prompts considerations for its clinical implications and future research directions. To harness the full potential of music in healthcare, clinicians could explore tailored music interventions for specific conditions, considering individual preferences and cultural backgrounds. Additionally, interdisciplinary collaborations between neuroscientists, musicians, and healthcare professionals can advance our understanding of the underlying mechanisms and optimize therapeutic applications. Moreover, investigating the long-term effects of sustained musical engagement and exploring innovative technologies, such as personalized music playlists, can enhance the efficacy of music-based interventions in diverse clinical settings. Future research should extend beyond music to examine the transferability of neuroplastic effects to other art forms and pleasurable activities, providing valuable insights into the broader implications for human health and wellbeing. While the neuroplastic effects observed in music may share similarities with other art-related pursuits, such as visual arts or dance, the intricacies of how specific brain regions respond to the emotional and cognitive nuances of different art forms remain an open question. It's essential to explore whether the structural and functional changes witnessed in music training extend to activities beyond music, shedding light on the broader implications for enhancing human health and wellbeing through various pleasurable pursuits.

5. Conclusion

The transformative power of music is due to its ability to influence the brain, promoting neuroplasticity, and bringing about changes that can benefit health and wellbeing. From pregnancy to old age, music can improve cognitive, emotional, physical, and social domains, making it a valuable tool for promoting health and treating disease. The potential of music to impact the brain in a positive way has led to the development of music therapy as a non-pharmacological intervention for treating various diseases. The insights gained from this literature review will aid in the development of more effective music-based interventions for promoting health and treating disease.

CRediT authorship contribution statement

Muriel T. Zaatar: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Kenda Alhakim:** Writing – original draft. **Mohammad Enayeh:** Writing – original draft. **Ribal Tamer:** Writing – original draft.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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