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Review article

Rhythmic musical activities may strengthen connectivity between brain networks associated with aging-related deficits in timing and executive functions

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ABSTRACT

Brain aging and common conditions of aging (e.g., hypertension) affect networks important in organizing information, processing speed and action programming (i.e., executive functions). Declines in these networks may affect timing and could have an impact on the ability to perceive and perform musical rhythms. There is evidence that participation in rhythmic musical activities may help to maintain and even improve executive functioning (near transfer), perhaps due to similarities in brain regions underlying timing, musical rhythm perception and production, and executive functioning. Rhythmic musical activities may present as a novel and fun activity for older adults to stimulate interacting brain regions that deteriorate with aging. However, relatively little is known about neurobehavioral interactions between aging, timing, rhythm perception and production, and executive functioning. In this review, we account for these brain-behavior interactions to suggest that deeper knowledge of overlapping brain regions associated with timing, rhythm, and cognition may assist in designing more targeted preventive and rehabilitative interventions to reduce age-related cognitive decline and improve quality of life in populations with neurodegenerative disease. Further research is needed to elucidate the functional relationships between brain regions associated with aging, timing, rhythm perception and production, and executive functioning to direct design of targeted interventions.

1. Introduction

The central premises of this review are that engagement in rhythmic musical activities may strengthen connectivity and synchronization between aging brain regions associated with timing, rhythm perception and production, and executive functioning. Brain aging affects networks important for executive functioning, timing, and musical rhythm perception and production (Ragot et al., 2002; Turgeon et al., 2011; Fjell et al., 2017; Tichko et al., 2022; von Schnehen et al., 2022). Timing is a critical aspect of executive functioning and perception of musical rhythm (Brown, 2006; Large and Snyder, 2009; Bååth et al., 2016). Brain aging is also a source of disability and decreased quality if life (Anton et al., 2015). Engagement in novel activities is associated with healthier brain aging and function (Mahncke et al., 2006; Park and Bischof, 2022). Interventions and activities which are enjoyable, effective, and economical are of interest due to the potential for increased access and sustained involvement. Learning and engaging in the production of musical rhythms may improve neurobehavioral mechanisms of timing and executive functions in older adults.

Several reviews account for the benefits of music on non-musical cognitive functions and brain aging (Benz et al., 2016; Ferreri et al., 2019; Kim and Yoo, 2019; Schneider et al., 2019). Other reviews report the significance of engagement with musical activities on emotional and social health in aging, as well as cognitive and motor benefits (Creech et al., 2013; Särkämö, 2018; Särkämö, 2019). Most recently, a review posited the potential for rhythm-mediated reward to increase learning, memory, and social connection (Fiveash et al., 2023). Considering the impacts of aging on the brain, cognition, and socialization over time (Dunphy, 1963; Carstensen, 1987, 1991, 1992; Cacioppo and Patrick, 2008; Cacioppo and Hawkley, 2009; Hasson et al., 2012; Nieuwenhuys, 2012; Schilbach et al., 2013; Cacioppo et al., 2014; Farajnia et al., 2014; Cacioppo et al., 2015; Hari et al., 2015; Schirmer et al., 2016; Kelly et al., 2017; Cacioppo and Cacioppo, 2018), it may be that music-based activities promote healthy social and cognitive functioning in older adults

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(Sutcliffe et al., 2020).

Despite the evidence on the uses of music-based interventions to address aging-related declines in cognitive, motor, and social understanding, little is known about the aging-related neurobehavioral interactions between timing, rhythm perception and production, and executive functioning. Furthermore, how these interactions may improve in older adults via participation in rhythmic musical activities is less well known. To address these gaps, this review presents potential brain-behavior relationships between aging, timing, rhythm perception and production, and executive functioning. The guiding research question was: what is the evidence of the relationship of aging to timing, musical rhythm and executive functions? Discussion is narratively based, following guidelines provided by Ferrari (2015). Studies were selected using handsearching (Hopewell et al., 2007). Search criteria were iteratively developed, including the following combinations of terms: “aging” AND “timing” AND “rhythm” AND “executive functioning.” Databases included PubMed and Google Scholar, with no filtering by year of publication. Selection and inclusion of studies were based off relevance to the research question and search criteria. Neither quality assessment nor formal data extraction using a systematic review manager (e.g., Covidence) were conducted.

Discussion begins with the neuropsychology of timing and rhythm, highlighting their overlapping neural correlates and potential relationships with executive functioning in aging. The discussion shifts to focus on relationships between brain aging, timing, rhythm, and executive functioning, positioning this information between the neuropsychology of timing and rhythm perception and uses of rhythmic musical activities to benefit cognitive aging. The latter section emphasizes the effects of individual and group music-based therapeutic interventions on the maintenance and improvement of executive functioning in healthy and cognitively-impaired aging populations. Finally, suggestions for future research are presented to address gaps in the existing literature around understanding if participation in rhythmic musical activities could strengthen the aging brain.

2. The neuropsychology of timing and rhythm

This section describes timing and rhythm from the perspectives of their measurement, perception and processing in the brain. Sub-sections include musical rhythm and language, and pleasurable experiences with rhythm to illustrate the potential for perception or production of musical rhythm to activate multiple regions of the brain. These overlaps in brain activation highlight the possibility for rhythmic musical activities to potentially assist in maintaining their healthy functioning.

2.1. *Describing musical rhythm*

Prior literature describes rhythm as a timed pattern of intervals within a framework of relative durations, suggesting short and long sequences of time as significant aspects of musical rhythm to which to synchronize to perceive and process it precisely and accurately (Schulkind, 1999; Bispham, 2006; Zatorre et al., 2007; Grahn, 2012; Levitin et al., 2018) Rhythm is experienced quite differently across cultures. This diversity is important to consider when designing rhythmic musical activities to address musical rhythm and its perception between participants with different cultural backgrounds (Hannon et al., 2012; Cameron et al., 2015; Will, 2017). How these cultural variations of musical rhythm and its perception apply to aging is not well understood. Furthermore, how these variations interact with the perception and production of musical rhythm in the aging brain is less well understood. Further work is needed to define and standardize conceptualizations of rhythm between cultures, as enculturation processes significantly affect experiences of rhythm (Hannon and Trehub, 2005; Polak, 2010), potentially having varying effects on relationships with timing and executive functioning.

2.2. *Describing timing*

Research in timing perception includes perceiving and differentiating discrete from duration-based events (Teki et al., 2011; De Pretto and James, 2015). Like musical rhythm, discrete events include sequential units of time (e.g., beats, pulses, or frequencies) often occurring within a larger framework, or duration-based event (e.g., a musical time-signature). It may be that as musical rhythms become more variable, i.e., more syncopated, the executive functioning required to attend precisely and accurately is greater. Interestingly, there is evidence to suggest an opposite association, that increasing age correlates with tapping synchrony in syncopated rhythms (Schirmer et al., 2020). How individuals dynamically attend to timing-based events significantly affects their ability to perceive and process incoming sensory stimuli into coherent understanding of their environment at a given moment in time (Large and Jones, 1999). It may be that increasing age affects how individuals dynamically attend to the timing associated with rhythmic musical stimuli, particularly considering declines in executive control throughout the aging process (Fjell et al., 2017). More work is needed to test associations between timing, rhythm, and executive functioning in aging to understand mechanisms, directionality, and normal distribution of skills in rhythm performance given a specific age range.

2.3. *Measuring timing and rhythm*

Wing and Kristofferson’s (1973) Morse telegraph key significantly shaped the measurement of timing and rhythm production by differentiating discrete and duration-based events. The Morse telegraph key allows for the recording of discrete events within a chain of inter-response intervals (Wing and Kristofferson, 1973). Inter-response intervals are the spaces between audible pulses presented at regular frequencies and volume levels. These intervals are mathematically and sequentially related, distributed across a range of time (e.g., 170–350 milliseconds) and further related based on motor response delays per participant in experimental paradigms. Tapping tasks emulating the Wing and Kristofferson (1973) model have been and are continuously used in the literature on timing perception across a spectrum of populations (e.g., Nozaradan et al., 2016; Bégel et al., 2017; Bégel et al., 2018).

Endogenous timing mechanisms (e.g., cerebellum, basal ganglia, and suprachiasmatic nucleus of the rostral hypothalamus) form representations of exogenously generated rhythmic stimuli (Ivry and Keele, 1989; Cohen et al., 1997). Experimental paradigms to determine neural correlates of rhythm and timing perception often involve measurement of sensorimotor synchronization through finger-tapping tasks (Repp, 2005). Importantly, beat (rhythm) and meter (time) perception have been shown to possibly involve different brain networks. Li et al. (2019) recruited healthy participants ($n = 31$; ages 19–23; 16 female) and used simultaneous EEG-fMRI to show greater activation of the supplementary motor area (SMA) in response to beat perception, whereas the putamen was more activated in response to meter. This dual-system perception of beat and meter is supported by evidence from other studies using different vocabulary (beat-based time for beat or rhythm, and duration-based time for meter), ultimately suggesting that the internal representation of time requires a complex, integrated network of structures to precisely and accurately perceive and process (Teki et al., 2011; De Pretto and James, 2015). Li et al. (2019) state that brain activity may have been confounded in their meter condition by participants remembering or imagining tapping the meter during training; a learning effect. Future studies need better controlled designs to minimize confounds in results.

Considering another relevant study, Teki and Griffiths (2016) discuss the role of working memory in the perception of auditory time intervals as “critical for accurate comprehension of natural sounds like speech and music.” In studying the effects of temporal jitter - variability in the length of a time interval around a mean value of inter-onset intervals -

and memory load of sequences containing various short duration clicks on working memory in younger neuropsychiatrically healthy adults ($n = 19$; 12 females; ages 25–29) using functional magnetic resonance imaging, Teki and Griffiths (2016) concluded that the cerebellum and striatum "represent core areas for representing temporal information in working memory." Limitations to their study included a small sample size, and biased representations of females and young participants. The block design for analysis of behavioral data and sparse sampling design of BOLD signal could affect interpretation of results. Their conclusion is important to the overarching story of this review: that affecting core brain areas responsible for timing and executive functioning (e.g., the cerebellum and striatum) may be beneficial to maintenance of cognitive functioning throughout the lifespan.

2.4. *Perceiving musical rhythm*

Perceiving musical rhythm may require both controlled and automatic processes, particularly in the context of short-duration sequences (Cohen et al., 1997; Fabio et al., 2019). The work of Patel and Iversen (2014) is important to highlight regarding perception and experience of rhythm. Their Action Simulation for Auditory Prediction hypothesis states that "simulation of periodic movement in motor planning regions provides a neural signal that helps the auditory system predict the timing of upcoming beats." This hypothesis associates with the Vuust and Witek (2014) application of their theory of predictive coding to musical rhythm, in which rhythm perception is conceptualized as an interaction between what is heard (rhythm) and the brain's anticipatory structuring of music (meter). Taken together with Levitin et al. (2018), who provide a comprehensive assessment of the relationships between rhythm perception and movement, there is substantive evidence to suggest that motor response to musical rhythm is inherent in the human perception and experience of rhythm. Therefore, physical engagement with musical rhythm may assist in extending functional connectivity between not only motor areas of the brain, but also coordination centers (e.g., cerebellum). This is critical to highlight regarding aging-related declines of motor control and executive functioning, and of the potential value of rhythmic musical activities to promote maintenance of those functions and cognitive independence (Seidler et al., 2010; Bernard and Seidler, 2014; Fjell et al., 2017; Degé and Kerkovius, 2018; Bugos, 2019; Muinos and Ballesteros, 2021; Landa, 2023).

2.5. *Neural correlates of timing and rhythm perception*

2.5.1. *A focus on the cerebellum and basal ganglia*

The cerebellum is responsible for mapping the coordination of space and time in both motor and perceptual timing, suggesting its central role in the hierarchical relationship of communication with the basal ganglia (Nozaradan et al., 2016; Caligiore et al., 2017). Substantial evidence supports the significance of the cerebellum and basal ganglia in timing and rhythm perception, as well as aging related declines in functional connectivity between these regions, and limbic and cortical structures (Ivry and Keele, 1989; Dreher and Grafman, 2002; Aparicio et al., 2005; Taniwaki et al., 2006; Molinari et al., 2007; Thaut et al., 2008; Seidler et al., 2010; Bernard and Seidler, 2014; Trost et al., 2014; Nozaradan et al., 2016; Caligiore et al., 2017; Fjell et al., 2017; Clark et al., 2019).

Aging affects event-related timing (Ragot et al., 2002; Turgeon et al., 2011), particularly as timing demands increase (Schirmer et al., 2020). However, cerebellar function may differentially affect aging-related timing deficits depending upon task-related demands, particularly differentiating event (e.g., finger tapping and intermittent circle drawing) from emergent (e.g., continuous circle drawing) timing demands (Ivry et al., 2002). Ivry et al. (2002) ran multiple studies testing stroke patients with focal cerebellar lesions (Study 1) and patients with bilateral cerebellar degeneration (Study 2) to age-matched controls. Overall, they demonstrated that compared to tasks requiring the patient groups to start and stop movement-related task demands, patients performed comparably to age-matched controls in a continuous movement circle drawing task, but with significantly greater variability in performing intermittent circle drawing and finger tapping. This finding was striking to the authors, providing for a potential differentiation of function in the cerebellum for event (start and stop) rather than emergent (continuous) timing. Indeed, this finding corroborates evidence outside of aging proposing the cerebellum as critical for error-correction in timing-based tasks (Teki et al., 2011). In addition, this finding supports evidence for a cortico-subcortico-cortical functional network synchronizing rhythmic time perception to entrained motor responses, where patients with cerebellar and basal ganglia lesions perform differently depending upon task demands specific to tempo (Nozaradan et al., 2017). It may be that adding continuation tapping tasks (i.e., removing the auditory stimulus to which to entrain one's tapping) as comparators could better differentiate understanding of effects of cognitively impaired and normal aging upon timing and time perception. To what extent participation or training may decrease declining event-related timing in the aging brain remains to be seen.

A recent review also highlights the role of the cerebellum in musicology, using historical examples of Western-music composers with damage to their cerebella as means to provide perspectives of the uses of music as a therapeutic tool to improve cerebellar function, as well as use of music as a probe to better understand cerebellar functioning in normal and diseased/damaged populations (Evers, 2023). These data support the need to further account for the effects of aging on the interactions between the cerebellum and basal ganglia during rhythmic musical activities, and to design interventions to minimize aging-related decline and subsequent effects on executive functioning.

Other work argues that the cerebellum is not limited to timing and execution of motor movements and control (Strick et al., 2009). Using a novel method of viral injection throughout the bodies of primates, Strick et al. (2009) show multiple projections of the dentate nucleus of the cerebellum to frontal, prefrontal, parietal, and cortical motor areas. The interconnections of the cerebellum with these areas suggest that impairments to these projections may affect cognitive, attentional, and emotional behaviors. Indeed, the functional topography of the cerebellum suggests its multi-faceted significance in controlled and automated behaviors, with cognitive (attentional and affective) control occurring in posterior regions (Schmahmann, 2019). In conjunction with Strick et al. (2009), and others (Koziol et al., 2012; Koziol et al., 2014), Schmahmann's (2019) formulation of cerebellar dysfunction into the cerebellar motor, vestibular, and cognitive affective syndromes suggest viewing the cerebellum as an integral part of executive control over both conscious and subconscious behaviors. As discussed earlier, perception and performance of musical rhythm requires coordination of both motor and cognitive systems, suggesting the significance of the cerebellum in these activities.

Timing perception is not limited to the cerebellum, however. Cohen et al. (1997) showed a distinct function of the suprachiasmatic nucleus (SCN) of the inferior rostral hypothalamus in not only disruption of circadian rhythmicity (e.g., diurnal functioning of multiple homeostatic requirements of mammals), but also short-duration timing events (e.g., motor implementation processes). Their work points to the hierarchic relationship between the SCN, cerebellum, and basal ganglia in both timing perception and motor implementation of short-duration timing, concluding that "a hierarchic relationship between long-duration (circadian) and short-duration timing exists, and that in addition to the cerebellum, intact hypothalamic functioning is necessary for short-duration timing" (Cohen et al., 1997). The authors studied AH, an individual with damage to the SCN to better understand the function of this region of the hypothalamus in moderating short-duration motor implementation processes using a motor continuation paradigm. They concluded that in contrast to age-matched and healthy controls, AH showed increased variability of both central timing and motor implementation, as well as duration discrimination, suggesting that these findings are in line with findings from prior work on the functional role of the cerebellum in short-duration timing (Ivry and Keele, 1989). Cohen et al. (1997) note that short duration timing depends on stable longer duration timing and that the SCN is not explicitly a short-duration clock but does have bearing on how drive and motivational signals from this region impact cognitive function and ultimately, timing. Application of this information to the healthy aging population may facilitate understanding of the significance of maintaining healthy function of the SCN to limit deficits in both long and short duration-based timing perception and processing.

2.5.2. *Other neural correlates of timing and rhythm perception and processing*

The healthy brain is functionally wired to operate in oscillatory patterns in response to rhythmic stimuli which appear fundamental to orchestrating complex cognitive processes and behaviors (Thut et al., 2012). Region-specific and network-wide connectivity across cortical and subcortical structures include roles of the striatum (Meck et al., 2008; Coull et al., 2011), motor and temporal cortices (Grahn and Brett, 2007; Bueti et al., 2008; Kornysheva et al., 2011; Bianco et al., 2017; Cona and Semenza, 2017; Slater et al., 2018; Gordon et al., 2018), arcuate fasciculus (Vaquero et al., 2018), corpus callosum (Rajan et al., 2019), and distributed networks across cortical and subcortical structures (Janata and Grafton, 2003; Thaut, 2003; Zatorre et al., 2007; Karabanov et al., 2009; Schwartze and Kotz, 2013; Herrojo Ruiz et al., 2014; Thaut et al., 2014; Amad et al., 2017; Agustus et al., 2018) in rhythm and timing perception and production.

Cortico-subcortical networks are implicated in the short duration timing of coordination of movement to an external auditory pulse (i.e., motor continuation via tapping paradigm) (Mayville et al., 2002). Mayville et al. (2002) were interested in brain networks responsible for coordination of motor systems in response to both syncopated (i.e., off-beat pulses) and non-syncopated (i.e., synchronized) auditory stimuli. The authors used functional magnetic resonance imaging to report that in response to both syncopated and non-syncopated beats, contralateral sensorimotor, caudal supplementary motor, and ipsilateral cerebellum were recruited, but syncopated stimuli also recruited the basal ganglia, dorsolateral premotor, rostral supplementary motor, prefrontal, and temporal association cortices. A small sample size ($n = 9$) and relatively broad age range (20–41) limit generalizability of the results. Further research is needed to confirm differentiation of activation of networks associated with syncopated and unsyncopated rhythms.

Similar findings to Mayville et al. (2002) using a different paradigm were reported by De Pretto and James (2015). The authors focused on differences between beat and duration-based sensorimotor synchronization (SMS) – an entrainment phenomenon associated with action-perception coupling of pertinent brain regions (Patel and Iversen, 2014) – showing that for duration-based synchronization, “participants reported higher attentional demands” suggesting recruitment of networks not necessarily involved in beat-based SMS. Recruited networks in both beat and duration-based SMS involved the bilateral superior temporal gyrus, supplementary motor area, and inferior frontal gyrus, left dorsal premotor cortex and primary motor cortex, and the right posterior cerebellum. A second brain network involved the bilateral basal ganglia, thalamus, inferior parietal lobes, and cerebellum. They conclude with the suggestion that of the two recruited networks, the first managed temporal information processing and execution of motor commands, while the second controlled error correction processing. However, a limitation to the study was ambiguity around whether participants used solely duration-based strategies during the condition requiring less attentional demands. Critically, duration-based SMS more strongly activated in both regions, suggesting that the higher attentional demands reported by participants link executive functions into duration-based SMS perhaps disproportionately to beat-based SMS. This is a significant finding toward application in research on aging, as older adults show functional declines in attentional processing (e.g., working memory and processing speed, Bernard and Seidler, 2014). It may be that participation in activities engaging regions of the brain responsible for attention and timing perception (e.g., rhythm synchronization tasks) may facilitate improved functioning in these regions throughout the aging process.

2.6. *Musical rhythm, language, and speech*

This section provides a brief account of studies on musical rhythm, language, and speech. Musical rhythm, language, and speech processing overlap in similar parts of the brain (Fadiga et al., 2009; Fujii and Wan, 2014), suggesting the potential to use rhythmic musical activities to benefit age-related language production deficits (Rossi and Diaz, 2016; Gollan and Goldrick, 2019).

The comparative studies between rhythm, timing, and language include discussion of rhythmic priming and audio-motor training affecting speech perception and music and grammar in language (Patel, 2003; Cason et al., 2015; Teki and Griffiths, 2016). Patel’s (2003) “Language, music, syntax and the brain” offers an evidence-base from which to understand similarities and differences between each communicative medium specific to syntax. The basis for Patel’s work emerged from a contradiction in the literature between neuroimaging data that suggested, 1) overlaps between brain regions responsible for syntactic processing in both music and language, and 2) neuropsychological data which suggested that linguistic and musical syntax could be dissociated. To address this contradiction, Patel provides a convergence of theories culminating in the hypothesis that music and language share brain machinery associated with syntactic processing and that due to this shared machinery, one may test the prediction that Broca’s aphasia would affect both language and music processing (Patel et al., 1998; Maess et al., 2001; Koelsch et al., 2002; Tillmann et al., 2003). Patel’s work provides theoretical grounding for addressing the age-related language production deficits previously mentioned (Rossi and Diaz, 2016; Gollan and Goldrick, 2019), though work in healthy aging using rhythmic musical activities to account for potential changes in interacting brain structures is lacking.

Use of syntax – defined as “a set of principles governing the combination of discrete structural elements (such as words or musical tones) into sequences” (Jackendoff, 2002, in Patel, 2003) – allows for comparison between language and musical rhythm because each communicative medium uses hierarchical structures to convey meaning, albeit within socio-cultural contexts. A recent meta-analysis found that the left inferior frontal gyrus, left supplementary motor area, and bilateral insula overlap in regard to linguistic and rhythmic syntactic processing, which the authors state as neural substrates involved in temporal hierarchy processing and predictive coding (Heard and Lee, 2020). Knowledge of these overlapping regions may assist in the design of novel rhythmic musical interventions to assist aging adults with language production and speech in noise perception deficits.

Transitioning to relationships between perception of prosody, particularly syllabic or rhythmic stress in music and language, Hausen et al. (2013) provide an original research study. The authors found that particular to rhythm perception in music and stress perception in speech, healthy Finnish adults (ages 19–60) with limited to no prior music education or training showed significant positive correlations on their performance of the Off-beat subtest of the Montreal Battery of Evaluation of Amusia (Peretz et al., 2003) and a word stress test translated into the Finnish language (Torppa et al., 2010). There were no significant findings reported between other elements of perception of prosody in music and language, such as pitch or scale perception, nor visuospatial perception. The authors cite Patel (2012) in stating that a resource sharing framework may indeed be responsible for overlap in the processing of rhythm in music and language, particularly between the right and left hemispheres. They further cite research from neuroscience and neuropsychology claiming the significance of the healthy functionality of multiple interacting regions (e.g., basal ganglia, cerebellum, supplementary motor area, and premotor cortex) in the processing of both speech (Kotz and Schwartze, 2010) and musical rhythm (Chen et al., 2008). Perhaps most interesting are potential transfer effects between speech and musical processing (Patel, 2011), which Hausen et al. (2013) relate to dynamic attention theory and synchronization between "internal oscillations and external temporal structure" (Large and Jones, 1999, in Hausen et al., 2013). Further research is needed to better clarify relationships between brain regions responsible for perception of prosody in music and language and performance on associated tasks. For Hausen et al. (2013), this is particularly important to potential visuospatial relationships between music and speech processing, as measurements of distributed networks responsible for attention and memory may offer means to correlate neuronal activity with neuropsychological assessment of both temporal and spectral (i.e., pitch or scale) domains.

2.7. Positive affect and musical rhythm

One of the associated responses to musical rhythm is positive affect (Blood and Zatorre, 2001). This might be relevant to the use of rhythmically rich stimuli and interventions in aging, as frequent positive affect may improve the likelihood of persistent engagement in an activity emphasizing findings from prior work stating improved executive functioning after longitudinal engagement in rhythmic musical activities (Lyubomirsky et al., 2005; Degé and Kerkovius, 2018; Bugos, 2019).

An aspect of positive affect is pleasure. Pleasure is a complex emotional construct that involves high levels of valence and arousal in response to musical rhythm (Blood and Zatorre, 2001). The neuropsychiatrically healthy individual has the capacity to temporally coordinate these complex emotional reactions and expressions in response to music across the entire brain and body (Brattico et al., 2013). This coordination may associate with induction of affect via rhythmic musical activities due to entrainment processes of the mind and body (Vuilleumier and Trost, 2015; Trost et al., 2017). Initial emotional reactions to highly rhythmic music involves heightened arousal, with effects of the autonomic nervous system stimulating synchronized changes in blood flow, pupil dilation, and muscle activation (Bowling et al., 2019).

Perception of musical rhythm stimulates the release and circulation of dopamine throughout the brain, emphasizing its association to movement and experience of pleasure from musical rhythm (Gebauer et al., 2012). A key factor involved with this outcome is musical anticipation (Huron, 2008). Synonymous terms with anticipation include prediction and expectation, which multiple authors have used specific to perception and processing of musical rhythm (Vuust and Witek, 2014; Salimpoor et al., 2015; Vuust et al., 2018). Coordinating rhythmic movements (e.g., dance) to external auditory cues (e.g., music) stems directly from pattern recognition and subsequent temporal predictions of incoming auditory stimuli (Salimpoor et al., 2015). Such coordination may involve interaction between multiple brain regions, suggesting the potential value of engagement with rhythmic musical activities on healthy cognitive functioning and brain aging.

3. Aging, timing, rhythm, and executive functioning

The review now focuses on associations between aging, timing, musical rhythm, and executive functioning. Sub-sections extend from discussion on the neuropsychology of timing and rhythm and direct attention to the potential neurobehavioral overlaps between timing, rhythm perception, and executive functioning. See Fig. 1 for a depiction of the associations between brain aging, the rhythmic brain, and cognitive processes associated with rhythm. As argued in this section, it

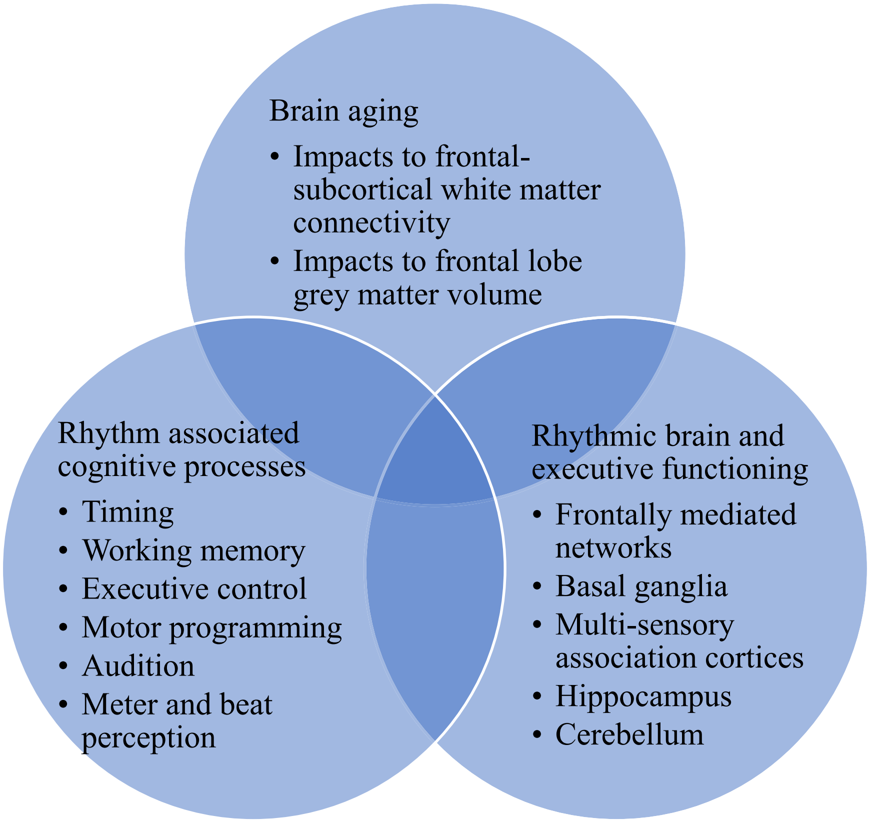

Fig. 1. Depicts proposed associations between brain aging, musical rhythm processing, and executive functioning. Rhythm is a complex task reliant on a broad, interconnected set of neural networks for optimal performance. Rhythm performance is both susceptible to degradation from brain aging and potentially valuable to engaging and improving the function of these networks.

may be that participation in rhythmic musical activities could strengthen connectivity between cortical and subcortical brain regions associated with timing and executive functioning due to the synchronization required to precisely and accurately perform rhythmic musical activities. This possibility is conceptualized elsewhere, exclusive of participation in rhythmic musical activities as the mechanism of action, considering synchronized brain rhythms as means to improved cognition (Grover et al., 2021).

3.1. Aging and executive functioning

Executive functions (EFs) are a group of top-down processes associated with concentration and paying attention (Diamond, 2013). EFs are associated with controlled processes, as opposed to automatic processes, with the former referring to effortful and deliberate retrieval of information relying on conscious behavior (Fabio et al., 2019). Three EFs are essential for concentration and paying attention: inhibition, working memory, and cognitive flexibility (Miyake et al., 2000). Inhibition refers to the ability to control attention, behavior, thoughts, or emotions in each moment; working memory is defined by the ability to make sense of information unfolding over time particularly when the information is no longer perceptually present; and finally, cognitive flexibility refers to the ability to fluidly change perspectives from spatial or social orientations (Diamond, 2013).

Alternative perspectives on executive functions expand from Diamond's (2013) and help to conceptualize application to, for example, musical rhythm perception. Nemeth and Chustz (2020) refer to EFs as functions that make us human, including working memory, attention, and processing speed. The authors build on the work of Branstetter (2014), who considered EFs as cognitive skills which regulate thinking, feeling, and behavior in pursuit of a goal. Focusing on working memory (WM) and attention, Oberauer (2019) described WM as the mechanisms or processes most needed to hold mental representations in real time, for the execution of an ongoing cognitive task. The author considered attention from two perspectives, one as a limited resource for information processing (Wickens, 1980), the other, a prioritization of information selection for processing (Chun et al., 2011). It may be that, in the contexts of aging and musical rhythm perception and production, one may find value in the maintenance of executive functioning to experience musical rhythm more fully.

Changes in motor control and executive function occur as a result of aging (Seidler et al., 2010; Bernard and Seidler, 2014; Fjell et al., 2017; Caballero et al., 2021; Ferguson et al., 2021; Veríssimo et al., 2022). In addition, the so-called disconnected brain view on cognitive aging states that older adults show declines in executive functions due to reductions in both structural and functional connectivity between the prefrontal cortex, basal ganglia, and striatum (Fjell et al., 2017). Interestingly, the findings of Fjell et al. (2017) suggest that the simultaneous activation of cortical and subcortical structures responsible for executive functioning may contribute to a deeper understanding of the disconnected brain view on cognitive aging. These findings provide for the possibility that engaging in activities rich in motor control and executive function over time may alter brain structure and function and lessen declines in these age-related changes, as corroborated elsewhere in persons living with ADHD (Slater and Tate, 2018). Rhythmic musical activities are known to improve motor control and executive functioning in healthy aging (Degé and Kerkovius, 2018; Bugos, 2019; Li et al., 2019), but a deeper understanding into the neurobehavioral mechanisms at play may assist in designing more targeted interventions to effect brain regions associated with these distinct but overlapping concepts.

3.2. Aging-related changes in executive functioning, timing perception and musical rhythm performance

Aging-related changes in executive functioning are associated with less precision and accuracy in the performance of musical rhythms, perhaps due to the relationship between aging and the decline in fastest regular tapping rate despite minimal changes to the ability to correct for timing error (Ragot et al., 2002; Turgeon et al., 2011). However, musical training may alter internal timing representation in older adults, suggesting potential benefits of longitudinal engagement in musical activities on brain networks associated with rhythm and timing perception (Fujioka and Ross, 2017).

Prior work supports the conclusion that increasing age decreases timing and event tracking, attentional processing, time estimation and temporal predictability (McAuley et al., 2006; Missonnier et al., 2011; Baudouin et al., 2019; Sauvé et al., 2019; Brinkmann et al., 2021). Sauvé et al. (2019) assessed differences between younger ($n = 14$; 18–25 years old; 7 females) and older ($n = 15$; 60–73; 10 females) adults' neural entrainment to varying tempi: slow, with 200 ms length and 200 ms interstimulus interval (onset between 400 ms to 2.5 Hz); and fast, with 100 ms length and 100 ms interstimulus interval (onset between 200 ms to 5 Hz). They utilized EEG steady-state frequency tagging and analyzed event-related potentials of neural entrainment to the fast and slow tempi between groups. They conclude that older adults' neural entrainment to the target frequency rates (2.5 and 5 Hz, respectively) was weaker than younger adults, providing support for the inhibition theory of aging, which argues that age negatively affects working memory and associated attentional processes (Hasher and Zacks, 1988).

Brinkmann et al. (2021) report similar results to Sauvé et al. (2019), studying how aging affects the neuronal signature of temporal predictability. They used electroencephalogram to compare results of neuropsychiatrically healthy younger ($n = 21$; mean age = 23.1 years) and older (n = 21; mean age = 68.5 years) adults who performed an auditory oddball task involving isochronous and random sound sequences. Older adults showed an altered P200 response, whereas younger adults showed variability in P50 amplitudes between the isochronous and random sound sequences. The authors suggest this result equates to less efficient sensory gating – a filter of sensory auditory information (Smith et al., 1994) – in older, but not younger participants.

Studies also suggest that aging is associated with changes in tapping rate, cognition, and neural anatomy (Schirmer et al., 2020). The authors recruited healthy older adults ($n = 70$; 58 female; mean age = 70.3 years) to measure tapping asynchrony and consistency using an existing paced-tapping task (Turgeon et al., 2016) and syncopated task (Escoffier et al., 2015), cognition using a battery of tests, and global and regional (cortical: auditory, premotor, paracentral; and subcortical: putamen, caudate, and cerebellum) gray matter volume and fractional anisotropy using MRI. Regarding tapping asynchrony, the authors found age effects on performance in both the unsyncopated and syncopated tasks. However, the authors state that the difference in performance between the tasks was not associated with age. They do state that increasing age lowered tapping consistency in the unsyncopated task, but not the syncopated task. Regarding gray matter volume (GMV) and regions of interest (auditory cortex), the authors report a negative relationship between age as the independent and GMV as the dependent variables in the cortex and subcortical matter. Regarding fractional anisotropy (FA), the authors report negative correlations between age and subcortical, but not cortical regions. These results infer that aging negatively affects brain structure, but not necessarily performance, as the authors reported surprising results regarding consistency being higher in the arguably more executively demanding syncopated tapping task. Further work is needed to clarify effects of aging on brain-behavior relationships specific to rhythm perception and production.

3.3. Uses of rhythmic musical activities to benefit cognitive aging

The diverse representation of brain regions associated with timing, rhythm perception and production, and executive functioning indeed suggest that aging not only negatively affects connectivity between associated brain regions, but also experiences with musical rhythm. As suggested in this section, maintenance of the anatomy and physiology of regions associated with control and automatic processes linked to timing, rhythm perception, and executive functioning may occur through participation in rhythmic musical activities. Such maintenance may improve healthy aging adults' experiences with musical rhythm, and potentially affect quality of life outcomes (Landa, 2023).

Broadly addressing music-based interventions and benefits to cognitive aging, cross-sectional evidence supports the conclusion that in individuals who self-report high levels of objective knowledge about music (e.g., formal music training, musical literacy, Western-trained music theory), their scores on assessments of episodic and semantic memory (i.e., Weschler Logical Memory Story A: Immediate Recall (LMI); Animal Naming Test (ANT) are higher than low-knowledge participants after longitudinal intervention (Gooding et al., 2014). Longitudinal evidence also suggests benefits to both cognition and mood in elderly individuals with an increased risk of falling (Hars et al., 2014). Further evidence for the role of music-making in healthy cognitive functioning is reported by Moussard et al. (2016). Using a Mann-Whitney U rank-order test, they found that musicians recorded fewer no-go errors ($U = (89)$, $p = 0.043$, $Mdn = 5.0$) in contrast to non-musicians ($Mdn = 7.5$), suggesting that music practice may benefit executive functioning throughout the lifespan. Recently, Wang et al. (2023) reported which neuropsychological assessments may better associate with effects of short-term musical instrumental training upon cognitive functioning in healthy aging adults, suggesting study design as a critical aspect of research on music-based interventions and potential benefits to cognitive functioning.

Specific to rhythmic musical activities, Biasutti and Mangiacotti (2018) reported pre-post improvements in cognitive functioning comparing rhythmic-music and music improvisation activities with a control group engaged in gymnastic activities. Participants ($n = 35$) were residents in a guest home and either living with mild-moderate cognitive impairment or healthy cognition. The intervention group ($n = 18$) engaged in 12 bi-weekly 70-minute group sessions of imitation, creation, and execution of rhythms using body and instrumental percussion to stimulate planning, attentional processes, anticipation, and emotive communication. Cognitive functions were assessed using the Mini-Mental State Examination (Folstein et al., 1975), verbal fluency and Trail Making test (Mondini et al., 2011), attentional matrices test (Spinnler and Tognoni, 1987), and the clock-drawing test (Tuokko et al., 1992). Pre-post results indicate significant improvements in the experimental but not control group for the MMSE, verbal fluency, and clock-drawing tests.

Longitudinal evidence also suggests that rhythmic musical training positively affects working and visual memory in healthy elderly adults (Degé and Kerkovius, 2018). Degé and Kerkovius (2018) compared the effects of a trained experimental group (drumming and singing) to untrained musical and literature-based control groups on working memory in healthy older adults. They used a longitudinal design (15 weeks) to assess changes in working memory across the groups, concluding that music training had a greater effect on visual memory in comparison to both control groups' performance in a symbol sequence identification task. The authors report several limitations for consideration in follow-up research, namely a small sample size ($n = 24$), unisex sample (all female), and need for a longer and more intense training program perhaps involving instrumental music-making, as they state that "singing and drumming are not highly musical-specific abilities" (p. 248). However, they encouraged the use of training protocols to which older adults may be attracted, to maintain interest and engagement in the tasks over the study period.

Support for benefits of long-term rhythmic musical training on working and visual memory comes from Bugos (2019). The author compared fine and gross motor synchronization in bimanual coordination between drumming and piano playing, with a music-listening control group to determine differences in effects of treatment on cognitive functioning. The author enrolled a significantly larger sample ($n = 135$) than Degé and Kerkovius (2018), offering greater statistical significance and generalizability. Enrolled participants achieved a score of ≥ 30 on the Telephone Interview for Cognitive Status and completed a baseline assessment of cognition across a spectrum of tests, including visual scanning/working memory, processing speed, verbal fluency, and response inhibition, as well as music aptitude and intelligence in advance of a 16-week training program involving three-separate 45-minute training sessions: 1) group piano; 2) group percussion; and 3) music listening. Participants were matched for age, education, and estimate of intelligence across the three groups. Results revealed a significant main effect of time for both visual scanning and working memory scores for both music training groups in contrast to the music-listening group. The author suggests including measures of musical achievement and/or motivation in follow-up research, as these outcomes can contribute to meaningfulness for participants and potential long-term participation. The author also reports the need to distinguish effects of bimanual coordination tasks more generally (e.g., juggling) on cognitive functioning from music-based bimanual coordination tasks, as the conclusions drawn may have been confounded by this variability.

There are also data suggesting uses of rhythmic music-based activities to rehabilitate speech-in-noise perception, as this is an issue faced by many elderly adults (Zendel and Sauvé, 2020). They performed a three-arm single-blind longitudinal training study involving participant randomization into a music training group (n = 13; mean age 67.5 ± 4.2 years; 10 females), video game group ($n = 8$; mean age 66.9 ± 3.9 years; 4 females), and no-contact group (n = 13; mean age 69.3 ± 5.7; 10 females) with assessments conducted pre (before intervention), mid (3-months into intervention), and post-training (6-months into intervention). All trainings were conducted in the comfort of each participant's domicile. Upon completion of the 6-month trainings, all participants were invited to a central testing space and fitted with an EEG-cap and presented with 150 French words spoken by a male voice in one of three conditions: without background noise, a quiet background noise setting (∼60 dB) and a loud setting (∼75 dB), with each of the latter two settings involving multi-talker babble noise specially recorded for the purposes of the experiment. Additionally, all three conditions were presented in either an active (i.e., participants repeated the word) or passive (i.e., participants ignored the word and watched a silent self-selected movie) setting. A mixed design ANOVA was used to analyze data where session (pre, mid, and post) and condition (no-noise, quiet, and loud) were within subjects factors and group (music, video, and no-contact) were between subjects factors. Results showed accuracy of repeated words in the active setting was negatively affected by noise level. Furthermore, accuracy in the music group improved from pre- to post-testing in the loud setting. The evidence presented by Zendel and Sauvé (2020) indeed provides for the takeaway that engaging with music throughout the lifespan may limit reductions in speech-in-noise perception, but inclusion of randomized controlled trials involving recruitment of larger sample sizes as well as cross-cultural comparative cohorts may increase the statistical significance of the effects of musical engagement on speech-in-noise perception.

Finally, there are data showing improvements in short term memory for faces after rhythmic training (Zanto et al., 2022). The authors conducted a longitudinal intervention-control study randomizing healthy aging non-musicians ($n = 47$; ages 60–79; 51 % female) to either a rhythmic training or word search-based training group. After eight weeks of in-home training (five days/week, 20-min each day), only the rhythmicity group showed significant improvements in short-term memory for faces. Additionally, the authors measured activity of participants' brains using EEG and found a significant role of the right superior temporal lobe in short term memory maintenance, as evidenced by enhanced decoding. See Table 1 for a review of studies focused on healthy aging, rhythmic musical activities, and executive functioning.

3.3.1. *Maintenance of physical independence in aging through rhythmic musical activities*

Research in aging includes the concepts of usual and successful

Table 1
A review of studies using rhythmic musical activities to address aging-related declines in timing and cognitive functioning in healthy adults.

Study	Participants	Methods	Outcomes	Limitations
Gooding et al. (2014)	*N* = 237; mean age = 77.4 ± 6.4; 67.1 % female; 7.6 % minorities	Non-randomized, cross-sectional design; linear mixed modeling to compare performance on musical knowledge survey with scores on semantic verbal fluency and episodic memory assessments	High knowledge participants had higher scores on the episodic memory, but not the semantic fluency assessment	Education levels may have confounded results; brain-behavior relationships need further attention
Hars et al. (2014)	*N* = 134; mean age = 75.5 ± 7; 96.5 % female	Longitudinal intervention/control design, where control was 6-month delayed intervention: music-based multitask exercise classes; pre-post neuropsychological test battery and mood assessment	Intervention participants showed improved mood in contrast to control group, and global cognitive performance improved with intervention overall	Trial was underpowered; treatment duration was short; eligibility criteria and trial sample as confounds
Biasutti and Mangiacotti (2018)	N = 35; mean age = 83.5 ± 6.95; 66 % female	Longitudinal intervention/control design, where control attended bi-weekly gymnastics and intervention was cognitive music training; pre-post neuropsychological test battery	Intervention participants improved on several cognitive functioning assessments in contrast to control group	Small sample size; only 12 bi-weekly sessions; low discriminative power in some tests; researchers were unblinded
Degé and Kerkovius (2018)	N = 24; mean age = 77 ± 3 months; all female	Longitudinal intervention/control design with two control groups to investigate effects of music training on working memory: intervention included drumming and singing, controls included literature training and normal activity	Musically trained participants remembered more words and were able to remember more symbol sequences correctly than both control groups	Only female participants; small sample size; training protocol was short and non-specific; analyses only affected alpha level; conclusions of longevity cannot be made
Bugos (2019)	N = 135; mean age = 68.62 ± 7 months; 72 % female	Longitudinal intervention/control design with piano and percussion as interventions, and music listening as control; standard battery of executive functioning	Intervention groups showed higher pre-post scanning/working memory scores compared to the control group; piano training most improved motor synchronization	Did not measure learning; practice logs were inconsistent; music training may not uniquely benefit executive functions; small sample size
Sauvé et al. (2019)	*N* = 29; 15 older (ages = 60–73 years, 10 female); 14 younger (age = 18–25 years, 7 female)	Cross-sectional within-subjects design involving slower and faster pure tone rhythmic sounds measured by electroencephalogram	Aging may decrease the ability of older adults to entrain to stimuli in the environment, supporting the inhibition theory of aging	Small sample size for between group comparisons; data could not best interpretation of reported results
Zendel et al. (2019)	*N* = 34; mean age = 67.9 ± 4.6; 71 % female	Longitudinal intervention/control design involving music training, video game, and non-contact groups to understand effects of aging on speech in noise perception using electroencephalogram	Engaging with music throughout the lifespan may limit reductions in speech in noise perception	Control group had high withdrawal rate; hearing status was poorly examined
Schirmer et al. (2020)	N = 70; mean age = 70.3 years; 83 % female;	Intervention/Control design involving paced tapping and cognitive functioning tasks, and measurement gray matter and fractional anisotropy	Results suggest aging preserves timing accuracy, but not timing reliability, as illustrated by structural and behavioral changes	Needed to measure sensory and motor functions; confounding comparison between periodic and syncopated tapping; age was nonuniformly distributed, potentially compromising power; focus on only one of two possible timing modes
Brinkmann et al. (2021)	*N* = 42; 21 older (mean age = 68.5 years, 15 females); 21 younger (mean age = 23.1 years, 13 females)	Cross-sectional within-subjects design involving an auditory oddball task of isochronous and random sound sequences measured by electroencephalogram	Older adults showed less efficient temporal sensory gating, which the authors interpret as a potentially negative influence on predictive adaptation behaviors	Did not disentangle whether observed age-related differences were based on quantitative or qualitative nature (i.e., nature of mechanism)
Zanto et al. (2022)	N = 47; ages 60–79; 51 % female	Longitudinal intervention/control design involving rhythmic training or word search training; short term memory for faces was assessed pre-post training; electroencephalogram measures were taken	Results conclude rhythmic training, not word search training, improved short term memory for faces; right superior parietal lobule implicated in enhanced training-related changes	No participants were able to perform at peak level in rhythm game; longer duration of rhythm training needed

aging, where successful aging underlines the imperative of physical independence as a marker of success (Rowe and Kahn, 1987; Guralnik and Kaplan, 1989; Anton et al., 2015). Participating in the production of rhythmic music requires substantial physical independence and continuing to play the drums, drum kit, or other percussion into late life may assist in the maintenance of physical independence, cognitive, emotional, and social health (Landa, 2023). The author discusses five reasons why drumming may be helpful for seniors, including a focus on how drumming keeps seniors active. She states the improvements for hand-eye coordination and motor control, providing benefit to healthy aging individuals and those with cognitive impairment or dementia. Landa's statements correlate with findings from Ekins et al. (2022), who recruited 26 older adults and randomized them to either a drumming and activities group or a hand-foot coordination group. After weekly sessions for thirty days and multiple pre-post physical (bar drop and chair rise tests, as well as 6-minute walk test, rate of perceived exertion, and assessment of balance) and physiological assessments (heart rate and blood pressure), the authors reported greater improvements in all assessments except balance. There were several limitations to the quality of Ekins et al. (2022) study design, including sample size and randomization. However, the results are promising regarding effects of group drumming on physical and physiological outcomes, perhaps with broader effects on cognitive functioning.

Though not explicitly musical, dancing is shown to improve motor and cognitive outcomes in aging adults (Kattenstroth et al., 2010; Douka et al., 2019; Noguera et al., 2020). Dancing is inherently rhythmical, requiring coordination among multiple brain and body systems to accurately execute movements (Muinos and Ballesteros, 2021). The authors' systematic review of the literature addresses if and how dance may counteract age-related cognitive, and brain decline in middle-aged and older adults. They claim that the motivational and emotional qualities of dance, as well as its adaptability to individuals' physical statuses and preferences may have protective effects on cognition in older adults. Combined with the aerobic and cognitive exercise required to precisely execute choreographed movements in social environments to music, there exist several reasons to suggest dance as an excellent means to assist in physical independence throughout aging. By engaging in the production of rhythmic music or participation in rhythmic musical activities like dance, older individuals can maintain aspects of their physical independence and address goals of successful aging, perhaps including maintenance of cognitive functioning. It may be that the maintenance of both physical independence and cognitive functioning better associates with successful aging than either component along (Joubert and Chainay, 2018). Thus, engaging in rhythmic musical activities may provide holistic benefits to aging adults capable of participating in both physically and cognitively demanding ways.

3.3.2. *A focus on neurodegenerative disease and rhythmic musical activities*

In populations with neurodegenerative disease, rhythmic auditory stimulation (RAS) and rhythmic auditory cuing (RAC) are common methods used to recruit spared cerebellar networks and enhance internal timing mechanisms that deteriorate from neuronal damage in the basal ganglia (Jones and Jahanshahi, 2014; Ashoori et al., 2015; Dalla, 2018; Devlin et al., 2019). Conclusions from Devlin et al. (2019) supported the efficacy of RAC in improving gait abnormalities. There is substantial evidence from studies of persons living with Parkinson's disease (PD) associating participation with or exposure to RAS or RAC with improved gait velocity, cadence, stride length, reduced falls, and temporal stability (Thaut et al., 1996; McIntosh et al., 1997; Thaut and Abiru, 2010; Nombela et al., 2013; Thaut et al., 2019). Persons living with PD show greater inter-network connectivity between executive control and motor/cerebellar networks compared to healthy controls, suggesting compensatory effects of temporally ordered auditory cueing on interactions between auditory, executive, and motor networks (Braunlich et al., 2019).

In contrast to RAS and RAC, music-based therapeutic interventions often target non-motor outcomes and have elicited improvements in cognition in patients with Parkinson's Disease, Alzheimer's disease, and related dementias (Fang et al., 2017; Barnish and Barran, 2020; Machado Sotomayor et al., 2021). Preferential music is known to elicit greater positive outcomes in cognition and behavior when compared to interventions with unfamiliar music (Leggieri et al., 2019). Fischer et al. (2021) designed a three-week intervention in which patients with Alzheimer's disease ($n = 14$; ages 56–88; 11 female) listened to long-known music daily for 1 h. Cognition was assessed before and after the intervention, and results showed significant improvements in the memory domain of the Montreal Cognitive Assessment.

As these areas of research continue to gain traction, it is important to note the relative absence of literature applying rhythmic musical interventions to patient populations with Alzheimer's disease and related dementias other than Parkinson's disease (e.g., fronto-temporal or vascular) and the lack of studies investigating changes of brain structure and function in response to these interventions (von Schnehen et al., 2022). However, recent studies suggest that rhythmic musical activity may positively affect socioemotional and motor response to music in inidividuals living with major neurocognitive disorder (Hobeika et al., 2021; Hobeika et al., 2022). Interestingly, Hobeika et al. (2022) report the potentially greater effect of tapping along with live music performance as opposed to sensorimotor synchronization to a metronome, suggesting in-person rhythmic musical activities as more efficacious upon socioemotional and motor outcomes. Future longitudinal studies should include investigation of potential changes in neurobehavioral outcomes associated with rhythm perception and production in healthy and pathological aging to better direct research design and application in this growing area.

4. Suggestions for future work

The evidence reviewed in this paper suggests that rhythmic musical activities may benefit timing perception and executive functioning throughout aging. What is less well known are the brain-behavior interactions between neural networks associated with timing, rhythm perception and production, and executive functioning (TREF) as humans age.

Clarification of terminology (e.g., discrete, event, duration, continuous) associated with musical rhythm perception and performance could help in designing more targeted interventions for healthy and pathological aging. This may particularly be the case for internally generated tempo-related adjustments to discrete (event) and duration (continuous)-based rhythmic timing, as evidence suggests that in individuals with cerebellar lesions, adjustments in tempo by 2 or 4 from a base tempo allows them to slow their perception of the groupings of beats, thus allowing them to better synchronize their movements to the beat (Nozaradan et al., 2012). Considering EEG-based findings for declining neurophysiological entrainment in older adults (Sauvé et al., 2019) and existence of distinct networks for event and continuous rhythmic timing using combined EEG-MRI (Li et al., 2019), it may be that longitudinal training in event-based rhythmic timing could improve neurologically impaired older adults' intrinsic and extrinsic neurobehavioral entrainment. Extending this work to healthy aging adults and including cognitive testing to determine potential associations between timing performance and executive functioning may generate more understanding into interacting neural components.

More research on musical rhythm, timing, and executive functioning is needed in samples of the healthy aging population. Such work would complement findings in populations with challenges from specific stroke lesions (Ivry et al., 2002; Nozaradan et al., 2017). This could enhance general understanding of identified relationships between rhythm, timing, and cognition and in the design of longitudinal interventions targeting these phenomena. Particularly, this could enhance general understanding of drivers behind aging-related declines in timing and executive functioning; whether timing declines drive declines in executive functioning, vice versa, or some yet unknown associations or causes. Furthermore, this could enhance understanding of uses of rhythmic musical activities to affect neural mechanisms of timing and executive functioning in healthy aging. Use of research to advocate for greater inclusion of rhythmic music making could further enhance potential benefits throughout aging, healthy or pathological, to reduce the scope and scale of aging-related declines in timing and executive functioning.

Execution of well-controlled studies is critical. Participants must be matched for age, education, music training, cognitive and health status, and cultural background. Controlling for these between participant differences will allow for greater generalizability across studies. Cultural background plays an essential role in the enculturation of rhythm perception (Hannon and Trehub, 2005; Polak, 2010). Due to the impact of culture on rhythm perception, there may be neurobehavioral overlaps in effects of culture on brain regions associated with TREF. How these variables interact in the context of healthy and neurodegeneratively-impaired aging would add significant context to the existing literature.

5. Conclusion

As this review demonstrates, aging is associated with declines in executive functioning, timing, and rhythm perception and production. Changes in functional connectivity between interacting brain regions associated with these phenomena may cause the resulting declines in behavioral outcomes demonstrated by older adults across a spectrum of timing-related studies. Deeper understanding of the neurobehavioral overlaps between executive functioning, timing, and rhythm perception and production may help to elevate existing study designs investigating uses of rhythmic musical activities to maintain or improve executive functioning throughout aging. By accounting for the overlaps between these topic areas, we provide means to amplify understanding of the positive effects of participatory rhythmic musical interventions on healthy brain aging. Concomitant literature on neurological rehabilitation in populations with dementia accounts for effects of engagement with group or individual music-based interventions on cognitive, physical, and social health. However, few well-designed and well-controlled interventions exist investigating preventive effects of rhythmic musical activities on functional declines in aging-related brain-behavior interactions. In addition, there is limited knowledge about the relationship of increasing age with changes in neurobehavioral synchronization associated with executive functioning, timing, and rhythm perception and production. Further research is needed to clarify and validate the effects of existing interventions and study results.

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Aaron Colverson: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Stephanie Barsoum:** Writing – original draft. **Ronald Cohen:** Conceptualization, Funding acquisition, Supervision. **John Williamson:** Conceptualization, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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