THESIS

COMPARING THE EFFECT OF RHYTHMIC AND MUSICAL CUEING ON A VOLITIONAL MOVEMENT IN OLDER ADULTS WITH PARKINSON'S DISEASE

Submitted by

Ryan Alexander Smith

School of Music, Theater, and Dance

In partial fulfillment of the requirements

For the Degree of Master of Music

Colorado State University

Fort Collins, Colorado

Summer 2021

Master's Committee:

Advisor: A. Blythe LaGasse

Andrew Knight
Brian Tracy

ABSTRACT

COMPARING THE EFFECT OF RHYTHMIC AND MUSICAL CUEING ON A VOLITIONAL MOVEMENT IN OLDER ADULTS WITH PARKINSON'S DISEASE

Music therapists who work from a neuroscience-informed approach use auditory cueing to facilitate movement exercises when working on motor goals with older adults with Parkinson's disease (PD). There is minimal research, however, comparing the effects of different auditory cueing techniques on the kinematic parameters of volitional arm movements in older adults with PD. Therefore, the purpose of this study was to compare the effects of auditory cueing types—no auditory cues, rhythmic cues, and sonified musical cues—on the movement smoothness and movement variance of repetitive, volitional arm movements in older adults with PD. Seven older adults with PD and ten college students completed three trials of a repetitive arm reaching task in each of three auditory cueing conditions. The position of each participant's wrist was recorded in three dimensions using an infrared motion capture system at 120Hz. Data from the kinematics system were processed to compute two indicators of movement performance–normalized jerk (NJ), an indicator of movement smoothness; and spatiotemporal index (STI), a measure of movement path variance–for each participant. No significant differences in STI or NJ were observed between groups in the no cueing condition. Between-condition analysis demonstrated a significant difference in NJ between the no cueing condition and rhythmic cueing condition such that NJ values were larger, and therefore movements were less smooth, in the rhythmic cueing condition. There were no statistically significant differences in STI between cueing conditions. Exploratory analysis, however, revealed that there is a trend

of decreased movement performance in the rhythmic cueing condition and improved movement performance in the sonified musical cueing condition for participants in the PD group. These findings were unexpected and warrant future research to determine which working mechanisms are the facilitators of change in auditory cueing-based rehabilitation of volitional movements.

ACKNOWLEDGEMENTS

First, I would like to express my gratitude to Dr. Blythe LaGasse for serving as my advisor and offering me the opportunity to work on this project. I appreciate you being open to my ideas while challenging me to be a better researcher and writer. The enthusiasm and humor you bring to research are traits I hope to emulate.

I would also like to thank Dr. Andrew Knight for helping me work through various research interests to find something that is valuable to the profession, meaningful for me, and feasible within the global situation. I appreciate that your feedback pushed me to connect my ideas to big-picture topics in music therapy.

My thanks to Dr. Brian Tracy for serving on my committee and helping me connect this project to the fields of motor control and exercise science.

I am grateful to Naomi Davis, Hannah Lentz, and Brianna Eskridge for beginning the project that became my thesis and for working with participants to collect kinematic data.

I would also like to thank the members of various thesis writing groups for their thoughtful responses to my writing. Thanks especially to Haley Crane, Shealyn Schmidt, and Daniel Morris.

Thank you to Dr. Nicole Niebuhr for providing insight into both the professional and human elements of academic writing.

Finally, I would like to extend my most sincere gratitude to my parents. Thank you for encouraging me to pursue my academic and personal passions. I am grateful for your support through challenging moments and for making sure I prioritized taking care of myself (and Coleman).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

Parkinson's disease (PD) is an age-related, chronic, and progressive neurodegenerative disorder caused by cell death in the substantia nigra pars compacta (SNpc), a basal nucleus located in the midbrain (Gutman, 2017). PD causes a decrease of dopamine in the brain, which leads to motor symptoms including tremors, bradykinesia, and rigidity (Gutman, 2017). Music therapists work with older adults with PD on goals including maintaining motor function. Music therapists may employ rhythmic cueing or the Neurologic Music Therapy (NMT) technique Patterned Sensory Enhancement (PSE) to help older adults with PD maintain or rehabilitate volitional and functional motor movements (C. P. Thaut, 2014). Although researchers have demonstrated improvements in motor movements in response to auditory cues (Thaut et al., 2015), there is little research comparing the effects of different types of auditory cues on motor rehabilitation or examining the neurological working mechanisms of cueing-based rehabilitation techniques. By better understanding these working mechanisms, music therapists may be able to refine and optimize auditory cueing techniques. The present study aims to determine the effects of different auditory cues on the kinematic parameters of a repetitive volitional arm movement in older adults with PD.

PD is caused by degeneration of dopamine-producing neurons in the SNpc. This degeneration leads to an insufficient concentration of dopamine in the nigrostriatal pathway. Dopamine in the nigrostriatal pathway is necessary for the regulation of voluntary motor function (Gutman, 2017). In older adults with PD, motor dysregulation manifests as a deficit of inhibition which leads to symptoms including tremors, rigidity, and a slowing of movement known as bradykinesia (Gutman, 2017). Early in the disease progression, older adults with PD experience tremors when an affected limb at rest. As the disease progresses, however, they may experience tremors while performing volitional movements (Mure et al., 2011; Pasquini et al., 2018). The combination of bradykinesia, rigidity, and tremors contributes to changes in kinematic parameters in older adults with PD (Dounskaia et al., 2009). Kinematic parameters that may be affected by PD include movement smoothness and movement path variance. These parameters may be operationalized and quantified using various validated measures, including normalized jerk (NJ) for movement smoothness and spatial-temporal index (STI) for movement path variance (Gulde & Hermsdörfer, 2018; Teulings et al., 1997).

Clinicians have treated the motor symptoms of PD with pharmacological and non-pharmacological interventions, including music therapy (Gutman, 2017; Thaut, 2013). Music therapists have worked with clients with PD to maintain motor functions that are necessary to complete activities of daily living and maintain independence (García-Casares et al., 2018). Music therapists may employ an NMT approach when working on motor skills with clients with PD. Therapists who work from an NMT approach implement formalized intervention techniques which are grounded in theories of neuroscience and music cognition (Thaut et al., 2014).

The NMT technique that is indicated for rehabilitation of volitional and functional motor movements in clients with neurological disorders is PSE (C. P. Thaut, 2014). Music therapists who facilitate PSE interventions manipulate the rhythmic, harmonic, melodic, and dynamic elements of music to create musical cues that are intended to represent and inform the temporal, spatial, and force elements of target movements. The process of providing an auditory cue that represents characteristics of a movement is known as sonification (C. P. Thaut, 2014). Researchers affiliated with NMT have suggested that sonified musical cues optimize kinematic outputs by proving the brain with an organized stimulus that allows the nervous system to structure, organize, and regulate complex movements (C. P. Thaut, 2014).

An alternate explanation for changes in motor outputs in response to sonified cues is that these changes are the result of entrainment to rhythmic elements of these cues (Thaut et al., 2015). Researchers have demonstrated improvements in motor functioning in response to rhythmic cues (Thaut et al., 2015), however the effects of spatial and force elements of sonified cues remains unexamined. Researchers have not compared the kinematic properties of movements facilitated by sonified cues to the kinematic properties of movements facilitated by rhythmic cues. It is therefore unknown if sonified cues contribute to different motor outputs than rhythmic cues. Research comparing motor responses to different auditory cues is critical to understanding the working mechanisms of auditory cueing-based motor rehabilitation.

There is a critical need to understand the function of musical elements within auditory cues in order for music therapist to optimize client motor outcomes and maximize their own clinical efficiency. Therefore, the purpose of this study is to compare the effects of auditory cueing types–no auditory cues, rhythmic cues, and sonified cues—on the movement smoothness and movement variance of repetitive, volitional arm movements in older adults with PD. The present study will address the following research questions:

R.Q.1: Do adults with PD demonstrate a difference in NJ of a self-paced volitional arm movement compared to adults without PD?

R.Q. 2: Is there a significant interaction between cueing condition and NJ of volitional arm movements in adults with PD?

R.Q. 3: Do adults with PD demonstrate a difference in the STI of a self-paced volitional arm movement compared to adults without PD?

R.Q. 4: Is there a significant interaction between cueing condition and STI of volitional arm movements in adults with PD?

CHAPTER 2. LITERATURE REVIEW

Parkinson's Disease

Parkinson's disease (PD) is a progressive neurodegenerative disorder that affects approximately 0.57% of the North American population age 45 and older, including an estimated 930,000 adults in the United States (Marras et al., 2018).

Pathology

The primary pathology of PD is neuronal cell death in the substantia nigra pars compacta (SNpc; Gutman, 2017). The SNpc is a basal nucleus located in the midbrain that produces the neurotransmitter dopamine. Dopamine has multiple functions in the brain, including modulating reward networks, promoting neuroplasticity, and regulating motor pathways in the basal nuclei (Gutman, 2017).

The basal nuclei are groupings of neuronal cell bodies in the midbrain that are involved in regulation of motor movement through excitation or inhibition of the cerebral cortex. There are three basal nuclei pathways; 1) the direct pathway, 2) the nigrostriatal projection, and 3) the indirect pathway (Knierim, 2020). The function of the direct pathway is to stimulate the cerebral cortex in order to initiate actions, including motor movements. The direct pathway begins with an inhibitory projection from the striatum, a region of the basal nuclei that consists of the caudate and putamen, to the globus pallidus internal. A projection from the globus pallidus internal then relays inhibitory signals to neurons in the thalamus. This signal is then relayed as an excitatory input to the cerebral cortex. The two inhibitory synaptic connections in this pathway create a net disinhibition, meaning that the excitatory projection from the thalamus to cerebral cortex is more active when the direct pathway is active (Knierim, 2020).

The nigrostriatal projection, another component of the basal nuclei networks, is an excitatory connection from the SNpc to the striatum. Synapses in the nigrostriatal pathway are driven by dopamine that is produced in the SNpc (Knierim, 2020). When the nigrostriatal projection is active, dopaminergic excitation of the striatum drives activity in the direct pathway. Parkinson's-related cell death in the SNpc reduces the availability of dopamine in the nigrostriatal projection, therefore decreasing activity in the direct pathway and allowing the inhibitory indirect pathway to regulate output from the basal nuclei to cortex via the thalamus (Knierim, 2020).

The indirect pathway is a basal nuclei network that results in inhibition of the cortex. The indirect pathway begins with inhibitory projection from the striatum to the globus pallidus external. A projection from the globus pallidus external subsequently inhibits the subthalamic nucleus. From the subthalamic nucleus, an excitatory projection synapses in the globus pallidus internal. An inhibitory projection then extends from the globus pallidus internal to the thalamus. From the thalamus, the indirect pathway shares a common output to the cortex with the direct pathway (Knierim, 2020). When the indirect pathway is predominant in this final projection, as is the case in people with PD, excitation of the cortex is decreased. Cortical input controlled via the indirect pathway results in less robust excitation of the cortex, which causes the symptoms of PD (Knierim, 2020).

Symptomology

PD affects multiple domains of function including cognition, sleep, (Feng et al., 2020), time perception (Schwartze & Kotz, 2016), communication, affect, and motor function (Gutman, 2017). The motor symptoms of PD tend to be the most pronounced and debilitating, such that PD is often labeled a movement disorder (Gutman, 2017). Hallmark motor symptoms of PD include tremors, bradykinesia, and rigidity (Gutman, 2017). Tremors that are present in the early stages of PD tend to be unilateral and occur when the affected area, often an upper limb, is at rest (Pasquini et al., 2018). As the disease progresses, however, tremors may occur during volitional movement of the affected limb, as well as additional areas of the body. Tremors that occur during volitional movements add complexity to the paths of these movements and reduce movement smoothness (Pasquini et al., 2018).

Bradykinesia is another motor symptom of PD. Bradykinesia is a slowing of motor movement that is caused by a decrease in the recruitment of neuromuscular motor units at the level of the cerebellar cortex. People who experience bradykinesia often need to execute multiple activation cycles of muscle groups in order to complete movements that people without PD execute in a single muscular activation cycle (Hallett & Khoshbin, 1980). This increase in the number muscle activation cycles means that the movements of people with bradykinesia are characterized by multiple accelerations and decelerations (Hallett & Khoshbin, 1980). Multiple accelerations within a single movement is an indicator of poor movement smoothness (Gulde & Hermsdörfer, 2018). In addition to affecting ongoing movements, bradykinesia is associated with a delay in the onset of muscle activation. This delay between the initiation of neural signaling and muscle activation further slows the motor response and contributes to functional disabilities associated with bradykinesia. Older adults with PD who experience bradykinesia also tend to demonstrate an acute, progressive decrease in motor velocity as a movement is repeated (Bologna et al., 2020).

Rigidity, the third hallmark motor symptom of PD, contributes to functional disabilities because older adults with PD may lack the range of motion necessary to complete activities of daily living (Gutman, 2017). Health care providers across multiple disciplines have developed a range of treatment options to help older adults with PD slow the progression of the disease and manage motor and non-motor symptoms.

PD Treatment

Pharmacological Therapies

The dopaminergic medication levodopa was introduced in the 1960s and remains the most prevalent pharmacological treatment for PD (Cilia et al., 2020). Levodopa is a chemical precursor to dopamine that is able to cross the blood-brain barrier and is converted to dopamine in the brain (Gutman, 2017). The transformation of levodopa into dopamine results in an increase of available dopamine in the brain. This increased dopamine concentration allows the nigrostriatal pathway to function more typically. Activity in the nigrostriatal pathway, in turn, increases activity in the direct pathway and ameliorates the motor symptoms of PD (Bologna et al., 2020; Cilia et al., 2020; Gutman, 2017). Levodopa treatment, however, has multiple limitations. First, the effects of the medication are short-term and peak in an "ON" phase within two hours of administration, then quickly subside. Additionally, patients taking levodopa tend to become less responsive to the medication over time (Feng et al., 2020; Gutman, 2017). The long-term effects of levodopa on the brain are not fully understood, however the drug has not been shown to reverse or stop neurodegeneration (Cilia et al., 2020). In an effort to mitigate these limitations, researchers have developed non-pharmacological treatments for PD.

Non-Pharmacological Therapies

One non-pharmacological treatment for PD is deep brain electrical stimulation via a surgically implanted device. Deep brain stimulation directly activates the basal nuclei and can improve motor function in older adults with PD while decreasing their reliance on dopaminergic medication (Gutman, 2017). Deep brain stimulation, however, is invasive and is not documented to affect the progression of PD (Gutman, 2017). Researchers and clinicians have therefore sought to develop treatments that are non-invasive, effectively ameliorate symptoms, and ideally slow or reverse neurodegeneration.

Researchers have found that various movement-based interventions show promise in decreasing the motor, emotional, and cognitive symptoms of PD, as well as physiologically protecting or restoring damaged neural circuits (Feng et al., 2020). Researchers have demonstrated the feasibility of using resistance exercise (David et al., 2012), aerobic exercise training, gait training programs (Feng et al., 2020), dance (Batson et al., 2016; Blandy et al., 2015), boxing (Morris et al., 2019), yoga (Cheung et al., 2018), and tai chi (Kim et al., 2014) to address PD symptoms. Exercise physiologists have suggested that the aerobic element of these interventions may promote neuroplasticity, improve neuronal function, and the promote the release of neurotrophic factors (Feng et al., 2020). These physiological changes may be working mechanisms that contribute to decreased motor and non-motor symptoms of PD and potentially slow the progression of the disease (Feng et al., 2020). The literature describing movement-based interventions, however, has considerable limitations. Researchers have only collected sparce data on the effects of so-called "complementary exercise" (Feng et al., 2020, p. 6) interventions such as yoga and boxing. Furthermore, the results of empirical studies of movement-based treatment approaches tend to be exaggerated in the popular press. Further research is therefore warranted to examine the validity and efficacy of movement-based therapies for PD (Morris et al., 2019).

In addition to long-term training effects, researchers have also indicated immediate motor benefits of exercise-based interventions for PD. These benefits include increased movement force and decreased movement variability (David et al., 2012). David et al. (2012) suggested that the mechanism underlying immediate changes in motor outcomes is the recruitment of additional motor units—systems of skeletal muscles and the nerves by which they are innervated. An increase in the number of active motor units may be independent of damaged basal nuclei pathways, meaning older adults with PD may experience the immediate motor advantages of preforming goal-directed movements (David et al., 2012). The goal-directed nature of movements in music therapy sessions may similarly contribute to immediate and long-term motor changes experienced by older adults with PD who receive music therapy services (Braunlich et al., 2019; Thaut et al., 1996).

Music Therapy

The American Music Therapy Association (AMTA, n.d.) defines music therapy as "the clinical and evidence-based use of music interventions to accomplish individualized goals within a therapeutic relationship by a credentialed professional who has completed an approved music therapy program." Music therapy interventions for older adults with PD can be divided into two major categories, relational and rehabilitative, which differ in both methods and goals (Raglio, 2015). Music therapists who work from a relational approach tend to work on goals in the psychosocial domain and employ a combination of receptive, recreative, compositional, and improvisational therapeutic musical experiences. A primary function of music in relational music therapy is to create a therapeutic relationship and environment that are conducive to clients working on their psychosocial goals (Raglio, 2015). Treatment models that fit into relational music therapy include humanistic, psychoeducational, psychodynamic, and wellness music therapy.

In contrast to relational music therapy, the goals of rehabilitative music therapy are to restore, maintain, or develop functional skills that are impacted by a disease or injury. The function of music in rehabilitative music therapy is to create structures and opportunities that facilitate the completion of a target behavior, as well as to promote physiological changes that may improve permanence on target behaviors (Raglio, 2015; Thaut et al., 2014). Neuroscience-informed music therapy is an example of a rehabilitative approach. Music therapists who practice from a neuroscience-informed approach consider the ways in which music perception and production affect the nervous system and develop interventions that leverage the influence of music on the nervous system to facilitate progress toward therapeutic goals. Neurologic Music Therapy (NMT) is an example of a rehabilitative and neuroscience-informed approach to music therapy (Thaut et al., 2014).

Neurologic Music Therapy

Neurologic Music Therapy is a formalized treatment approach in music therapy that consists of 20 therapeutic music techniques designed to meet client needs in the sensorimotor, communication, cognitive, and psychosocial domains (Thaut et al., 2014). Clinicians and researchers design NMT techniques and other neuroscience-informed music therapy interventions using the Transformational Design Model (TDM; M. H. Thaut, 2014).

The TDM is a process through which researchers and interventionists identify the techniques and exercises used to meet client objectives in non-music based therapy and adding music as a functional element to structure, organize, or facilitate the execution of a target behavior. M. H. Thaut (2014) referred to the process of creating threptic music experiences as an isomorphic translation from a non-musical to a musical intervention. The purpose of the TDM is to ensure that musical interventions directly address the target behavior, that music is a core functional element of interventions, and that therapeutic outcomes generalize to non-musical settings. For example, a music therapist working on a motor goal may add musical cues to an exercise that has been prescribed by a physical therapist. By applying the TDM to motor goals, clinicians developed and formalized NMT techniques that are indicated for use in motor rehabilitation with older adults with PD. These techniques are Rhythmic Auditory Stimulation (RAS; Thaut & Rice, 2014) and Patterned Sensory Enhancement (PSE; C. P. Thaut, 2014).

Rhythmic Cueing and Rhythmic Auditory Stimulation

Rhythmic cuing is the use of periodically regular external auditory prompts to promote motor and speech outcomes. Music therapists who use rhythmic cueing provide a predictable temporal stimulus that indicates the timing of a movement. Rhythmic cueing is the basis of RAS, a protocolized NMT technique in which clients perform a series of gait exercises that are facilitated by rhythmic cues. Interventionists select and modulate the cadence or tempo of rhythmic cues for each client in order to optimize their unique gait pattern (Thaut & Rice, 2014).

An established literature supports the use of rhythmic cueing for gait rehabilitation in adults with PD (Devlin et al., 2019; Ford et al., 2010). Thaut et al. (1996) found that adults with PD demonstrated increased velocity, stride length, and cadence following an RAS gait training program but not following a gait protocol that did not include auditory cues. In a literature review on the effects of music-based intervention on movement disorder symptoms, Devlin et al. (2019) indicated that the authors of five empirical studies found improvements in velocity, cadence, or stride length in response to rhythmic cueing. Likewise, Nombela et al. (2013) reviewed 10 studies, each of which demonstrated velocity, cadence, or stride length benefits of gait training with rhythmic cues. Pau et al. (2016) increased the measurement precision of spatiotemporal parameters of gait using infrared camera motion capture. In addition to previously documented improvement in velocity, stride length, and cadence, Pau et al. (2016) found that participants demonstrated a decrease in the duration of the double support phase of gait following RAS, which suggests that participants were less reliant on double support to maintain stability. Furthermore, Pau et al. (2016) analyzed kinematic data and computed quantitative indicators of variability of movement patterns in individual joints and suggested that rhythmic cueing contributed to decreased variability in hip flexion.

Use of motion capture to identify changes in specific gait components supports the validity of using quantitative kinematic parameters to detect motor differences in auditory cueing research. In addition to the documented benefits of RAS gait training on spatiotemporal and kinematic parameters of gait, researchers have suggested that RAS may improve movement quality indicators including freezing of gait (Nieuwboer et al., 2007), variability in muscle activation (Thaut et al., 1996), falls, and cadence variability (del Olmo & Cudeiro, 2005; Devlin et al., 2019; Nombela et al., 2013).

Researchers have also published preliminary evidence that suggests rhythmic cueing may also be beneficial in non-gait motor rehabilitation. For example, Thaut et al. (2002) examined the effects of rhythmic cueing on reaching movements of hemiparetic upper extremities in stroke survivors. Thaut and colleagues found that the timing of movements was less variable in a rhythmic cueing condition than in an un-cued condition. This research team also found that participants' movement trajectories were less variable and velocity profiles were smoother in the rhythmic cueing condition than the un-cued condition. Together, these findings suggest that auditory rhythmic cues may contribute to kinematic stability and optimized motor output of upper extremity movements. Additionally, the method and results published by Thaut and colleagues demonstrated the validity of using kinematic analysis of motion capture data to examine upper extremity motor responses to auditory cueing.

The extant literature indicates that music therapists use rhythmic cueing, among other techniques, to address motor needs in adults with neurological movement disorders. There is a lack of literature, however, examining the effects of rhythmic cueing and other auditory cueing techniques on upper extremity movements in older adults with PD. Specifically, there is a dearth of research comparing the effects of rhythmic cueing to other music therapy techniques, such as PSE.

Patterned Sensory Enhancement

Patterned Sensory Enhancement is an NMT technique that is indicated for rehabilitation of motor function in clients with neurological and orthopedic needs (C. P. Thaut, 2014). Music therapists use PSE to target two primary goals: 1) to improve physical characteristics of movements including strength, endurance, balance, and posture, and 2) to rehabilitate specific functional movement sequences of the upper limbs (C. P. Thaut, 2014). The goals music therapist implement PSE to address are distinct from the goals addressed with RAS because music therapists employ PSE to target and improve non-intrinsically rhythmic movements. These non-intrinsically rhythmic movements include volitional upper extremity movements and complex movement sequences. The primary methodological distinction between PSE and rhythmic cueing is that, when implementing PSE, music therapists deliberately incorporate multiple musical elements, in addition to rhythmic cues, into auditory cues in order to structure and facilitate the target movement (C. P. Thaut, 2014).

When implementing PSE, music therapists incorporate purposefully selected rhythmic, melodic, harmonic, dynamic, and timbral elements into musical cueing patterns. These musical elements are hypothesized to function as temporal, spatial, and force cues that represent the properties of the target movement. C. P. Thaut (2014) suggested that the timing, muscular force, and spatial displacement of movements may be represented by a “musical gestalt” (p. 106) that is created by music therapists to represent and train specific motor patterns. The process of creating and presenting a musical cue that represents a motor movement is known as sonification (C. P. Thaut, 2014). For example, the temporal elements of a sonified musical cue for bicep curls may involve a predictable duple meter at a moderato tempo to represented the temporal boundaries of each repetition.

Spatially, the melody of a sonified cue for bicep curls may ascend to indicate the lift phase of the movement and descend to represent the controlled lowering phase. In order to indicate force in this sonified cue, a music therapist may play harmonies that imply tension, such as dominant chords, during the ascending phase of the movement and harmonically resolve to represent the relative decrease in muscular force required during the descending phase. A music therapist may also use dynamic contrast to represent the force of a bicep curl by playing a crescendo through the ascending phase of the movement and a decrescendo during the descending phase. C. P. Thaut (2014) suggested that, through sonification, musical cues may serve to regulate neurological and muscle activations an optimize the execution of target movements. It should be noted that it is not clinically typical for a music therapist to include all of the sonification elements listed above into a PSE experience. Clinically typical PSE involves rhythmically predictable chordal facilitation on piano or autoharp with the dynamics and direction of the chords representing the force and spatial element of the target movement. Music therapists often sing familiar melodies over this chordal facilitation.

Although researchers have conducted observational studies on the effects of PSE, there is liminal empirical support to suggests that musical elements that contribute to the "musical gestalt" (C. P. Thaut, 2014, p. 109) neurologically represent movements or contribute to improved motor outcomes. Specifically, there is a lack of literature that examines differences in motor responses between PSE and other auditory cueing conditions.

Researchers have conducted observational research on the effects of PSE on exercise adherence, observer-rated range of motion, observed temporal synchrony with the movement facilitator, and execution of exercise technique (Clark et al., 2012; O'Konski et al., 2010; Yamada, 2009). Results from these existing PSE studies have seldom indicated differences in parameters of interest between PSE and other auditory conditions or exercise formats. For example, O'Konski et al. (2010) compared the effects of PSE to a background jazz recording on four visually observed parameters of exercise execution in a sample of residents at long-term care facilities. Of the 76 comparisons the researchers completed (four outcome parameters for each of 19 exercises), only three comparisons–the number of repetitions completed in sync with the facilitator for three exercises–were found to be significantly higher in the PSE condition than the background jazz condition. Similarly, Yamada (2009) used a between-groups design to compare the effects of PSE to non-PSE music on exercise adherence among healthy older adults and found no significant between-group differences in the number of repetitions completed, direction of movement, range of motion, or overall exercise execution. Also consistent with these findings, Clark et al. (2012) found that participants demonstrated no significant difference in exercise adherence or perceived exertion between PSE sessions and exercise sessions without music.

Collectively, the extant PSE literature indicates only scant differences in movement quality between PSE and other movement facilitation techniques. Furthermore, the outcomes presented by Clark et al. (2012), O'Konski et al. (2010), and Yamada (2009) are related to the endurance, strength, and postural goals of PSE, rather than the rehabilitation of specific movement patterns. These general goals are often addressed in populations of older adults without diagnosed neurological movement disorders using clinically typical PSE. It is therefore unknown if the results of these studies are generalizable to neurorehabilitation populations with whom music therapists may work on functional motor sequence rehabilitation goals. Further research is warranted to examine the effects of PSE on motor outcomes in neurorehabilitation settings. This future research may utilize increasingly accessible quantitative measurement and analysis techniques to perform more sensitive comparisons of motor parameters between cueing conditions. Kinematic analysis of motion capture or wearable device data may be among such techniques.

Kang et al. (2020) used wearable movement trackers to examine the effects of different auditory cues on kinematic properties of a shoulder abduction, hold, and adduction task with stroke survivors. The researchers found that the angle at which participants held their shoulder in the hold phase of the task was more consistent in a melodic cuing condition that incorporated concepts of spatial cuing that are characteristic of PSE than in an un-cued condition and a rhythmic cueing condition. The researchers did not, however, find significant kinematic differences during active movement phases. Although Kang and colleagues interpreted their results as suggesting an advantage of melodic cueing for motor rehabilitation, they only observed differences in the hold phase, during which the melodic cue consisted of a single pitch repeated as quarter notes for eight beats. These results do little to suggest that melodic contour contributed to the observed movement differences. Further examination of the potential clinical implications and working mechanisms of musical cueing are therefore warranted.

Proposed Working Mechanisms of NMT Techniques

Music therapy clinicians and researchers who work from a neuroscience-informed approach are interested in understanding the neurological working mechanisms that contribute to the effects of music-based interventions in order to develop new techniques and optimize existing techniques. In the NMT approach, researchers and clinicians follow the Rational-Scientific Mediating Model (R-SMM) to theorize and examine the neurological working mechanisms of music-based interventions (Thaut et al., 2014). The goal of the R-SMM is to promote understanding of the neurological activity involved in functional skills, music perception, and music production. Researchers mediate, or consider the similarities between, the neurological activations of musical and functional non-musical skills. The premise of mediation is that engaging in musical experiences that use shared or extended neural networks to those used in functional skills may be utilized to alter or re-train neurological pathways involved in these skills. Working under this premise, NMT clinicians develop therapeutic musical experiences that are intended to activate specific neural networks in order to help clients habilitate or rehabilitate target skills (Thaut et al., 2014).

Researchers have suggested four conceptual frameworks that may contribute to the effects of auditory cues in motor rehabilitation; 1) entrainment, 2) priming, 3) motor plan monitoring, and 4) engagement (Clark et al., 2012; Thaut et al., 2015). Within each of these frameworks, researchers have further suggested specific patterns of brain activation, or neurological working mechanisms, that may contribute to the motor effects of auditory cues. Researchers have implicated networks involving numerous cortical, subcortical, cerebellar, and brainstem structures in auditory-motor responses. Activation of these networks are potential neurological working mechanisms underlying auditory cueing (Crasta et al., 2018; del Olmo et al., 2006; Schwartze & Kotz, 2016; Thaut et al., 2015). The specific neural networks through which entrainment, priming, motor plan monitoring, and engagement effect movement patterns, however, have not been thoroughly explored (Braunlich et al., 2019; Devlin et al., 2019).

Entrainment. Researchers have frequently identified the conceptual framework of rhythmic entrainment as a possible explanation for the effects of rhythmic cueing and PSE on motor rehabilitation. Entrainment is the capacity of, and tendency for, periodic events known as oscillators to synchronize their temporal period in order to optimize their efficiency (Thaut, 2013). The phenomenon of entrainment applies to cueing-based rehabilitation because neuronal firing in the human nervous system function as an internal oscillator that has the capacity to entrain to the period of an external oscillator, such as an auditory cue (Nombela et al., 2013; Thaut, 2013; Thaut et al., 2002). Grahn and Watson (2013) suggested that the basal nuclei may be directly activated by rhythmic stimuli and may be the neurological locus of entrainment. Direct activation of the basal nuclei may compensate for damage to basal nuclei structures in older adults with PD and contribute to more typical motor function. Neurological evidence for this proposed stimulation of the basal nuclei, however, is scant. Rather, numerous researchers have suggested that the neurological working mechanism of entrainment is temporally predictable recruitment of un-damaged compensatory neural resources (Braunlich et al., 2019; Devlin et al., 2019; Mainka, 2015).

Thaut et al. (2015) proposed that the neurological working mechanism of entrainment is temporally predictable activation of motor circuits via neural networks that are involved in auditory processing and independent of damaged basal nuclei pathways. The theory underlying this proposed mechanism is that damage to the basal nuclei affects time perception and interferes with time-based signals from the basal nuclei to motor regions of the cortex. Researchers have implicated basal nuclei structures including the putamen in time perception (Nombela et al., 2013; Schwartze & Kotz, 2016), suggesting the validity of Thaut's (2015) premise. Drucker et al. (2019) observed that adults with PD exhibited reduced activation of the striatum. When the putamen–a part of the stratum–does not receive adequate dopaminergic input from the SNpc, adults with PD may experience deficits in time perception that may contribute to deficits in motor performance and motor sequencing (Ashoori et al., 2015; Cameron et al., 2016; Schwartze & Kotz, 2016). Therefore, if a compensatory extended neural network is able to deliver temporally predictable neural signals, similar to those from the basal nuclei, to motor areas of cortex, motor symptoms of PD may be ameliorated.

As a time-based stimulus, rhythmic or musical cues may, through entrainment, promote activation of proposed non-basal neural networks that convey timing information (del Olmo et al., 2006; Schwartze & Kotz, 2016). Rhythmic cues may help the brain compensate for decreased putamen function by facilitating time perception and time-linked neuronal firing in non-basal brain regions including the premotor cortex, supplementary motor area (SMA), medial cortical areas, and cerebellum (Grahn & Brett, 2007; Grahn & Watson, 2013; Nombela et al., 2013; Pecenka et al., 2013; Stegemöller, 2018). If time-constrained stimulation from any of these proposed areas is the sole working mechanism underlying auditory cueing-based rehabilitation, these networks would be active in both rhythmic cueing and PSE. Therefore, an absence of motor differences in response to different auditory cueing conditions would suggest that entrainment of temporally responsive compensatory networks may be the neurological working mechanism behind entrainment, as well as auditory-motor responses more generally. The existence of connections between auditory and motor brain regions is foundational to the neurological plausibility of entrainment via non-basal compensatory networks as a working mechanism of auditory cueing in motor rehabilitation.

Numerous researchers have suggested that a connection is present between the cortical auditory system and the cortical motor system, particularly the SMA (Ashoori et al., 2015; del

Olmo et al., 2006; Mainka, 2015; Nombela et al., 2013; Schwartze & Kotz, 2016). Grahn and Brett (2007) used functional magnetic resonance imaging (fMRI) to examine the nature of auditory-motor connections that have been proposed as being involved in rhythmic entrainment. These researchers reported that participants showed greater activation in the SMA during a motor task in a metered cueing condition than a non-metered cueing condition. Grahn and Brett (2007) interpreted these findings as an indication that beat perception increases activation in the SMA. A coupling between the auditory system and the SMA would suggest that information processed by the auditory cortex is relayed to motor areas with intact temporal fidelity, meaning that the timing of an auditory cue would be represented in the neural signals that reach the SMA.

Crasta et al. (2018) supported the idea of temporal fidelity of neural signals by demonstrating that auditory-related and motor-related neural oscillations are sequential and coupled. Neural signals from the auditory cortex to the SMA may facilitate time-constrained motor functions via a pathway that does not involve the basal nuclei and would therefore likely be unaffected by PD (Ashoori et al., 2015). Researchers have not reached a consensus, however, as to the role of the proposed auditory-SMA network in rhythmic cueing and suggested that additional neural resources, including the cerebellum, may be functional elements of auditory cue-based rehabilitation (Braunlich et al., 2019).

Drucker et al. (2019) demonstrated that the cerebella of older adults with PD were active during a tactile-cue based repetitive motor task. These researchers suggested that the cerebellum may function as a compensatory extended network by regulating the pace of motor function when the basal nuclei are damaged (Drucker et al., 2019; Schwartze & Kotz, 2016). Furthermore, there is a documented connection between the SMA and cerebellum such that researchers sometimes discuss these neural components together as the cerebellar-SMA loop or motor-cerebellar loop (Nombela et al., 2013). Devlin et al. (2019) suggested that rhythmic stimuli may activate the cerebella of older adults with PD, thereby bypassing damaged timing mechanisms in the basal nuclei and regulating motor output through the cerebellar-SMA loop. del Olmo et al. (2006) found that adults with PD demonstrated increased activation in the right anterior lobule of the cerebellum following four weeks of gait and finger tapping training with rhythmic cueing. These results suggest that rhythmically entrained activation of the cerebellum may be a neurological working mechanism of cueing-based motor rehabilitation, including rhythmic cueing and PSE. Researchers have not reached a consensus, however, as to whether differential activations in the cerebella of older adults with PD are compensatory or pathological (Schwartze & Kotz, 2016). A null difference in motor responses between PSE and rhythmic cueing would suggest that temporally-sensitive compensatory networks such as the motor-cerebellar loop are the working mechanism underlying both PSE and rhythmic cueing. Researchers have not reached a consensus, however, as to the role of specific brain regions in entrainment.

Stegemöller (2018) suggested that PD may cause damage to the SMA in addition to the basal nuclei. Therefore, a function of rhythm in rehabilitation may be to reduce the brain's reliance on the SMA for motor planning by providing precise timing signals and recruiting compensatory pathways for movement initiation. Although Stegemöller (2018) did not specify the neural pathways by which auditory signals may reach the SMA, she suggested that rhythmic cueing may contribute to more precise motor timing by allowing the SMA to activate at closer and more predictable intervals to the onset of a movement. This predictable activation is an example of entrainment of the SMA to a rhythmic cue.

Braunlich et al. (2019), however, did not concur that a connection between the auditory cortex and SMA may be a working mechanism in rhythmic cueing for motor rehabilitation. These researchers did not find an effect of rhythmic cueing on motor-cerebellar networks and therefore suggested that auditory-motor connections are not a primary driver of motor responses to auditory cueing (Braunlich et al., 2019). One possible explanation for the discrepancy between the results of Braunlich et al. (2019) other research teams, including Grahn and Brett (2007), are differences in the paradigms research participants completed. The rhythm reproduction task used by Grahn and Brett (2007) likely evoked cognitive processing, which may have activated the frontal lobes, thereby introducing a potential mediating brain area into the proposed auditory-motor connection.

Entrainment and cognition. Although Braunlich et al. (2019) did not find evidence of a connection between the auditory and motor systems, they did find evidence to support the existence of a connection between the auditory system and frontal lobe executive networks, as well as between frontal lobe executive networks and the motor system. This sequence of connections documented by Braunlich et al. (2019) implies that, rather than a direct connection between the auditory cortex and SMA, the frontal lobe executive networks may be an intervening node in the proposed auditory-motor network. If executive networks mediate auditory-motor networks, the concept of rhythmic entrainment, as it is currently conceived, may be less vital in music-based motor rehabilitation than has been previously proposed. If frontal lobe executive networks are involved in the amelioration of the effects of PD, music therapists may seek to prioritize providing musical supports that produce the optimal activation in the frontal lobes, rather than providing a stimulus to which the brain can entrain.

Optimized activation in the frontal lobes may be achieved by modifying the cognitive load necessary to process and respond to auditory cues. Izbicki et al. (2020) demonstrated motor-evoked potentials in the brain may be of different amplitudes in different musical conditions. This lends validity to the concept of differing arousal in the frontal lobes between auditory cueing conditions. Rhythmic cues are relatively simple and therefore require a low cognitive load to process. Comparatively, sonified PSE cues are complex and require a greater recruitment of cognitive resources to process. If frontal lobe activation is a working mechanism of auditory cueing, the differences in cognitive loads necessary to process rhythmic cues and sonified cues may manifest in differences in motor output between these cueing conditions. Furthermore, if motor outputs are different between rhythmic cueing and sonified cueing, this may indicate that the frontal lobe executive system responds differently to these cues.

Frontal lobe cognitive involvement in the processing of auditory cues may explain why older adults with PD respond differently to auditory cues as the disease progresses. As the cognitive symptoms progress, people in later stages of the disease may have difficulty processing complex stimuli such as sonified cues (Lindaman & Abiru, 2013). Older adults in the later stages of PD may therefore respond best to rhythmic cueing because it provides the optimal cognitive load. If the validity is found for the cognitive model of auditory-motor responses, further research would be needed to examine the cognitive loading effects of different cue types in the brains of older adults in different stages of PD progression.

The executive-motor connection suggested by Braunlich et al. (2019) may explain why internally generated musical cues such as mental singing may contribute to motor improvements (Harrison et al., 2019). Harrison et al. (2019) found that older adults with PD demonstrated an increase in gait variability in a musical cueing condition and a decrease in gait variability in a mental singing condition, both compared to an un-cued gait condition. If internally generated cues are produced in the frontal lobes, signals from the frontal lobes may drive activation in motor areas using the same executive-motor network as the auditory-executive-motor pathway implied by the findings of Braunlich et al. (2019). Pecenka et al. (2013) lent validity to the premise that frontal lobe-produced stimuli may affect the motor system by implicating the medial prefrontal cortex in cognitive processing of responding to changes in a rhythmic stimulus. Furthermore, internally generated cueing may produce a more optimal level of cognitive arousal than external musical cues.

Priming. Priming of the motor system is another conceptual framework that may contribute to understanding the neurological working mechanism or mechanisms of rhythmic cueing and PSE. Priming refers to neurological activity that occurs in anticipation of an action (Thaut et al., 2015). Thaut (2013) suggested that priming puts the brain in a state of readiness to move and therefore may increase the quality of subsequent motor responses. Activation of the SMA approximately 100 milliseconds before an expected rhythmic stimulus, as suggested by Stegemöller (2018), is an example of nervous system priming.

In addition to anticipatory neurological activations associated with a single event, researchers have suggested that priming also occurs over larger time scales in the range of minutes (Braun Janzen et al., 2019; Crasta et al., 2018). Braun Janzen et al. (2019) suggested that the working mechanism of priming is activation of a central time keeping mechanism in the brain. Braun Janzen et al. (2019) suggested that, once a timing mechanism is active, it remains primed and contributes to improvements in other movements. For example, an older adult with PD may prime the central time keeper by tapping their finger to a rhythmic cue. This priming may then contribute to improve gait parameters (Braun Janzen et al., 2019).

Crasta et al. (2018) used time-frequency analysis of electroencephalography (EEG) data to examine the neurological correlates of auditory-only and motor-only priming. These researchers found that auditory priming was associated with a decrease in the power of delta, alpha, and low beta (4 – 20 Hz) neural oscillations during a rhythmically cued tapping task. Crasta and colleagues suggested that this decrease in the power of slow oscillations may represent an optimization in the efficiency of neurological networks involved in motor outputs on subsequent trials. The authors labeled this increased efficiency of cortical activation as "repetition priming" (Crasta et al., 2018, p. 111). The neurological efficiency associated with repetition priming may be the working mechanism underlying the effects of rhythmic cueing and PSE on motor outputs.

Motor Plan Monitoring. Thaut (2013) proposed that temporal constraints imposed by rhythm may allow the brain to form motor plans that are completed within the period of a beat. Neurological activations required to perform goal-directed and time-limited tasks may stimulate activity in the brain that helps overcome or bypass damage caused by PD, traumatic brain injury, stroke, or other neurological conditions (Braunlich et al., 2019; Thaut, 2013). Because the brain is able to predict the onset of a rhythmic stimulus (Stegemöller, 2018), the brain may be able to compare the physical position of the body in an ongoing motor movement to the temporal position within a beat. The brain may then modify the neural motor plan by sending signals to the muscles to change the rate or trajectory of the movement in order to complete it within the period of the beat. For example, bradykinesia or movement freezing may cause an older adult with PD to execute a motor movement more slowly than the ideal motor plan. If, for example, the brain recognizes that the arm is 25% of the way to a target when 50% of a constraining beat has elapsed, the brain may recognize this disparity and send neural signals to the muscle to increase the velocity of the movement.

In this example, the rhythmic stimulus increases the specificity of the motor plan template. This increased specificity may allow the cerebellum to more efficiently compare the rate, range, and force of an ongoing movement to the rate, range, and force of the motor plan. The cerebellum may then send signals to motor areas of the brain in order to make necessary modifications to signals sent to muscles. This real-time motor plan monitoring may help people with PD execute movements within a predictable period, thereby overcoming the motor symptoms of the disease (Thaut, 2013; Thaut et al., 2015). If motor plan monitoring based on the temporal predictability of an auditory stimulus is the primary working mechanism of rhythmic cueing and PSE, researchers could expect that the motor outcomes of these techniques would be indistinguishable because both rhythmic cues and sonified PSE both contain a temporally predictable beat stimulus. In addition to rhythm, researchers have suggested that pitch processing may be involved in motor plan monitoring (Kang et al., 2020).

Kang et al. (2020) suggested that non-rhythmic musical elements may be involved in motor plan monitoring. These researchers hypothesized that the tonotopic organization of auditory regions of the brain may relate to perception of the body in physical space. Kang et al. (2020) did not suggest a neurological network that could relate pitch information to proprioceptive and motor monitoring systems. In order to achieve the proposed pitch-space relationship, a neural network would relate the firing of frequency-specific cells in the auditory system with the activation of neural networks involved in proprioception and motor monitoring. There is negligible neurological evidence for the existence of neural networks that might facilitate such a connection.

Engagement. Engagement is another conceptual framework that may help researchers understand the neurological working mechanism of auditory cueing-based rehabilitation. Music may promote engagement in the therapeutic process and this engagement may contribute to better treatment motivation and execution of therapeutic exercises. Mainka (2015) suggested that the musical gestalt of sonified cues promotes attention to the cueing stimulus. Similarly, Grahn and Watson (2013) called for an examination of the potential effects of musical concepts on engagement. These concepts include client preference, genre, and the level of musical energy. Beyond incorporating attentionally salient musical elements within rhythm cues, Street (2012) suggested using an eclectic approach to addressing neurological needs in music therapy. Street (2012) reported a case study in which he used rhythmic cueing to promote gait rehabilitation and songwriting to promote therapeutic engagement. He suggested that increased engagement from non-motor experiences contributed to success on motor outcomes.

Cameron et al. (2016) suggested that older adults with PD may have better beat perception in a musical context than a non-musical context, stating "additional information in real music may give listeners with PD sufficient cues regarding the beat" (p.6). The authors do not, however, indicate what musical elements may be the source of this "additional information" (p.6). Increased engagement may be involved in the proposed beat perception advantage within music because older adults with PD may be more likely to attend to a musical stimulus than a metronome. Additionally, the presence of multiple musical elements may provide older adults with PD multiple potential sources of beat information, such as a vocal line or a bass line.

If engagement is a working mechanism of rhythmic cueing and PSE, there would likely be differences in the motor outcomes between these techniques. These motor differences would likely include better motor performance in a PSE condition because sonified cues are widely considered to be more engaging than rhythmic cues. Despite the emphasis placed on engagement by numerous music therapy researchers, C. P. Thaut (2014) did not discuss engagement in the initial hypothesis regarding the effect of the musical gestalt on motor performance.

Working Mechanism Summary. Few of the conceptual frameworks and specific neurological working mechanisms described above suggest a function of non-rhythmic musical elements or spatial and force cues in motor rehabilitation. Furthermore, proposed working mechanisms are supported by inconsistent levels of empirical research. Researchers have therefore not reached a consensus as to whether multi-element musical cues contribute to differences in motor function compared to rhythmic cueing alone (Raglio, 2015).

Regardless of the working mechanism or mechanisms that underly rhythmic cueing and PSE, the goal of these techniques is to improve motor function by improving brain function. It is therefore relevant to consider how neuroplasticity, or changes in the brain, occurs. Neuroplasticity is the capacity for the brain to make structural changes to promote learning and compensate for damage (Stegemöller, 2014). Neuroplasticity may involve the formation of new synapse or the reorganization of entire neural pathways (Stegemöller, 2014). Older adults with PD may benefit from increased neuroplasticity because the process of plasticity may help compensatory neural networks, such as those described in the sections above, become more permanent. Researchers have demonstrated that music listening promotes activation in dopaminergic regions of the brain and that dopamine promotes neuroplasticity (for review see Stegemöller, 2014). Sonified cues and rhythmic cues may produce different concentrations of dopamine in the brain and therefore differences in neuroplasticity. Although neuroplasticity is not directly a working mechanism of rhythmic cueing and PSE, this framework may contribute to differences in the generalizability of the outcomes of these techniques. If, for example, the sonified cues contribute to a greater dopamine concentration than rhythmic cues, more plasticity may occur and contribute to PSE being more generalizable than rhythmic cueing.

There is a need for quantitative methods to examine the effects of rhythmic and musical cueing techniques on the motor system in order better understand the working mechanisms that contribute to these effects. Kinematic analysis of motion capture data is an established and valid tool in movement studies.

Motor Kinematics

Motion Capture

Motion capture is a technique in which the position of anatomical locations of a participant's body are recorded by a system of cameras, markers, and computers. Prior to beginning a motion capture recording, researchers place reflective markers at designated points on the participant's body. The purpose of the reflective markers is to ensure that the motion capture system consistently detects anatomical locations of interest. Cameras in the motion capture system detect infrared light that is reflected by the markers and the computer determines the location of each marker at each recording interval—typically more than 100 times per second. The output of a motion capture recording is a table of the coordinates, in three dimensions, of each marker at each capture interval. Researchers use these data to quantify characteristics of the recorded movement, including velocity, acceleration, jerk, joint angles, movement variability, and movement path (Isenberg & Conrad, 1994; Mündermann et al., 2006).

Movement Smoothness

Movement smoothness is a vital kinematic parameter in neurorehabilitation because smoothness is thought to reflect the ability of the nervous system to form and execute a motor plan (Gulde & Hermsdörfer, 2018). Thaut (2013) theorized that the benefits of auditory cueing are in part attributable to the formation and monitoring of motor plans. Movement smoothness measures may therefore be sensitive to motor changes that occur in response to auditory cueing. Furthermore, smooth movements are more efficient and may contribute to safer completion of activities of daily living in older adults with PD. Measures of movement smoothness may therefore indicate rehabilitative progress and predict functional motor outcomes.

Researchers use three primary approaches to determine the smoothness of a movement; velocity-based, acceleration-based, and arc length-based parameters (Gulde & Hermsdörfer, 2018). Jerk is an example of an acceleration-based movement smoothness parameter. Jerk is the mathematical derivative of acceleration, meaning that the summed value of jerk within a time interval represents the change in acceleration within that time interval. An optimally smooth movement would have a jerk value of zero because movement accelerations would occur at constant rate. In kinematic analysis of complex human movement patterns, however, jerk is detectable and has been documented as a valid and sensitive measure of movement smoothness (Gulde & Hermsdörfer, 2018).

Researchers have used normalized jerk (NJ, Teulings et al., 1997) as a parameter with which to compute and report jerk in kinematic research with multiple neurologic population, including PD (Alberts et al., 2000; Romero & Stelmach, 2003; Romero et al., 2003), stroke (Konieczny et al., 2020; Rohrer et al., 2002), cerebral palsy (Aboelnasr et al., 2017), and Autism Spectrum Disorder (Fukui et al., 2018). The result of NJ analysis is a unitless quantitative indicator of summed jerk that is normalized for path length and duration.

In auditory cuing research, differences in NJ between auditory cueing conditions would indicate changes in smoothness that may be attributable to the auditory cues. Peng et al. (2011) used NJ to examine the effects of PSE on sit-to-stand movements in children with cerebral palsy.

They found that participants exhibited lower NJ scores during sit-to-stand repetitions that were facilitated by PSE cues as compared to an un-cued condition.

Movement Variance

In addition to movement smoothness, researchers have used indicators of movement variance to assess the kinematic properties of movements (Smith et al., 2000). Movement variance parameters are numerical indicators of the consistency of movement paths across multiple repetitions. Spatiotemporal index (STI) is one parameter of movement path variance (STI; Smith et al., 2000). Researchers calculate STI by creating a model of average movement path for all repetitions of a movement and then taking the sum of standard deviations of each repetition from this model. This sum of standard deviations, STI, is a unitless numerical indicator of movement variance in which a smaller number represents less variance, which is an indicator of healthy neuromuscular output (LaGasse, 2013; Smith et al., 2000). Researchers have used STI to examine the variability of oral motor output in various conditions including different utterance lengths (Sadagopan & Smith, 2008) and speech rates (Smith et al., 1995). LaGasse (2013) used STI to examine the effects of rhythmic cueing on trajectory stability of oral motor movements, thereby establishing the validity of STI as an outcome parameter in auditory cueing studies.

Kinematic Characteristics of PD

The motor symptoms of PD, including tremors, bradykinesia, and rigidity, contribute to decreased movement smoothness and increased movement variability (Gutman, 2017; Viviani et al., 2009). Isenberg and Conrad (1994) established a connection between bradykinesia and decreased movement smoothness by demonstrating that adults with PD exhibited multiple velocity peaks within each repetition of a slow movement. Multiple velocity peaks is indicative of poor movement smoothness and suggests that participants with PD required multiple muscle activation cycles to complete each repetition of the task (Gulde & Hermsdörfer, 2018; Hallett & Khoshbin, 1980). Viviani et al. (2009) and Romero et al. (2003) further linked bradykinesia and movement smoothness by demonstrating that adults with PD who experience bradykinesia demonstrated reduced motor fluidity during handwriting-like tasks and line-drawing tasks respectively. These differences between older adults without a neurologic diagnosis and older adults with PD demonstrate that movement smoothness is affected by PD more than it is affected by typical ageing. Kinematic parameters of smoothness and variability may therefore be valid tools to assess the efficacy of interventions on motor symptoms in adults with PD.

Purpose and Research Questions

The motor symptoms of PD contribute to quantifiable kinematic changes and functional disabilities. Music therapists who work from a neuroscience-informed approach may use rhythmic cueing and/or PSE to help older adults with PD restore or maintain motor function. Understanding the working mechanisms of these techniques may help music therapist select and refine therapeutic musical experiences by providing cues that promote optimal neurological activations. The motor responses to, and neurological working mechanisms of, auditory cueing have not been thoroughly explored. Specifically, researchers have not compared the effects of rhythmic cues and sonified PSE cues on volitional movements in older adults with PD. Differences in motor responses to rhythmic and sonified cues may imply that the neurological working mechanisms of PSE are distinct from the neurological working mechanisms of rhythmic cueing.

Within-participant analysis of movement smoothness and movement variability may indicate differential effects of auditory cueing conditions. Kinematic differences in motor responses to rhythmic cues and sonified musical cues may suggest that musical elements other than rhythm recruit distinct neural resources to regulate motor patterns, as proposed by C. P. Thaut (2014). Kinematic differences between auditory cueing conditions may also imply that different cueing conditions contribute to different cognitive loads. The purpose of this study, therefore, is to compare the effects of auditory cueing types—no auditory cues, rhythmic cues, and sonified musical cues—on the movement smoothness and movement variance of repetitive, volitional arm movements in older adults with PD. This study will answer the following research questions:

R.Q.1: Do adults with PD demonstrate a difference in NJ of a self-paced volitional arm movement compared to adults without PD?

Hypothesis 1: There will be a significant difference in NJ of a self-paced volitional arm movement between adults with PD and adults without PD.

R.Q. 2: Is there a significant interaction between cueing condition and NJ of volitional arm movements in adults with PD?

Hypothesis 2: There will be a significant interaction between cueing condition and NJ in adults with PD.

R.Q. 3: Do adults with PD demonstrate a difference in the STI of a self-paced volitional arm movement compared to adults without PD?

Hypothesis 3: There will be a significant difference in STI of a self-paced volitional arm movement between adults with PD and adults without PD.

R.Q. 4: Is there a significant interaction between cueing condition and STI of volitional arm movements in adults with PD?

Hypothesis 4: There will be a significant interaction between cueing condition and STI in adults with PD.

CHAPTER 3. METHOD

Participants

A convenience sample of older adults with Parkinson's Disease (PD) (*n* = 7; 5 female, 2 male; 2 left handed) ages 68 to 82 (*M* = 74.9, *SD* = 4.43) were recruited based on their participation in PD exercise and vocal health groups at a University music therapy clinic. Additionally, a convince sample of college students (CS, *n* = 10; 7 female, 3 male; 1 left handed) ages 19 to 21 (*M* = 19.9, *SD* = 0.74) were recruited as a comparison group. Movement patterns change with normative aging (Dixon et al., 2018) and therefore the researchers anticipated that groups would be non-equivalent. The researchers also intended to include a sample of older adults with no neurological disorders, however data collection was stopped due to restrictions in response to the COVID-19 pandemic.

The inclusion criterion for participants in the PD group was to have a primary diagnosis of PD. Inclusion criteria for the CS group was to be at least 18 years of age, have no documented hearing impairment, and have no diagnosed movement or neurological disorder. All participants who were recruited completed the study procedure and were included in all data analyses (see Figure 1).

Design

The present study used two non-randomized, quasi-experimental, 2x3 factorial analyses. Participants in both the PD and CS groups completed three trials of a repetitive arm reaching task under each of three auditory cueing conditions. The independent variables in both designs were group (PD and CS) and auditory cueing condition (no cueing, rhythmic cueing, and sonified cueing). In the first design, the dependent variable was normalized jerk (NJ), a measure of movement smoothness. In the second design, the dependent variable was spatiotemporal index (STI), a measure of movement path variance. Parameters of movement smoothness and movement path variance were calculated from the same raw data.

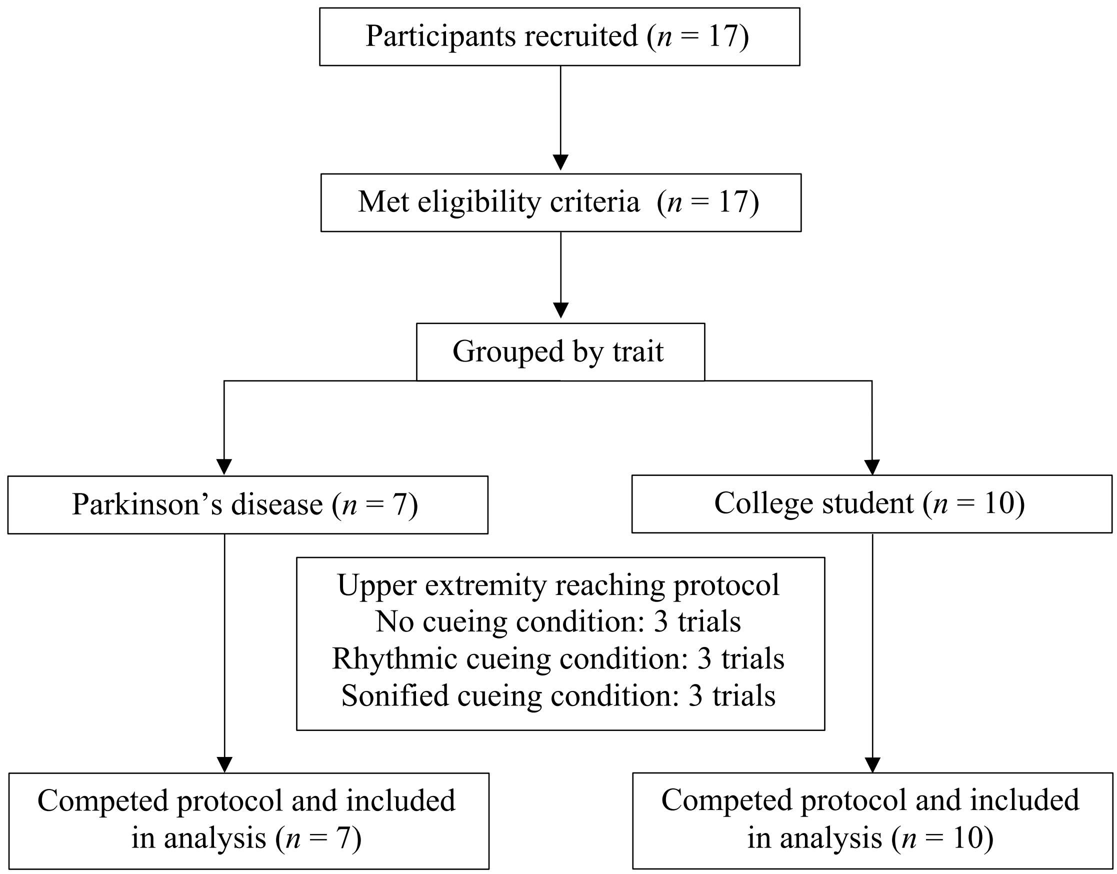

Figure 1. *Participant Flow Diagram*

Materials

Motion Capture System

Upper extremity movements were recorded using a six-camera OptiTrack Infrared Motion Capture System (NaturalPoint Inc., Corvallis, OR, USA). Motion capture cameras were arranged in two columns such that three cameras to the participant's and three cameras were to their right. The center camera in each column was aligned with the participant in the frontal plane. The additional cameras in each column were located in front of and behind from the center camera (see Figure 2).

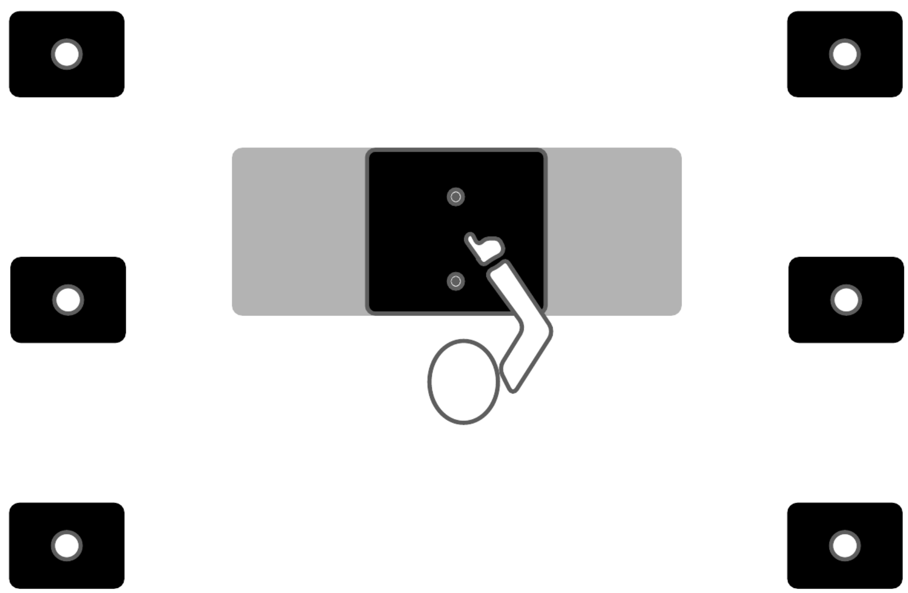

Figure 2. *Experimental Setup and OptiTrack Camera Arrangement*
Note. This figure is not to scale. Rectangles with circle in the center represent OptiTrack cameras.

The OptiTrack system recorded the position of infrared-reflective markers that were placed by research assistants at the participant's shoulder, elbow, forearm, wrist, knuckle of the middle metacarpal, and pointer finger phalangeal knuckle. Motion capture data were output as coordinates of each marker in the x, y, and z axes at a rate of 120 Hz. Only data from the wrist maker were analyzed in the present study.

Target Board

A black plywood board (approximately 30 in x 30 in) with holes drilled on a 2 in x 2 in grid and placed on top of a table was used to provide endpoint targets for the arm reach task. Target discs were affixed to holes in the board. For this study, the proximal target was placed 12 inches from the proximal edge of the board and in the center sagittal plane. The distal target was placed in the same sagittal plane as the proximal target and 12 inches further away from the participant (see figure 2). The target board was sloped slightly toward the participant at a 15° angle.

Audio System

A research assistant played pre-recorded auditory cues using a computer with two external speakers. The speakers were placed approximately 8’ in front of the participant and offset to the participant’s left and right. Before each participant completed arm movement trials, a research assistant checked the volume of the audio system to ensure that the participant was able to hear the auditory cues clearly without them being too loud.

Rhythmic Cueing Track

For trials in the rhythmic cueing condition, a research assistant played a track of a digital metronome set to 70 beats per minute (BPM). The researchers selected a cueing rate of 70 BPM because it is near the low end of the range at which adults can entrain (Rose et al., 2019). Participants who experience bradykinesia are therefore likely able to complete each repetition of the movement within the period of one beat.

Sonified Cueing Track

During sonified cueing trials, a research assistant played a pre-recorded of a well-known folk tune arranged for piano at 70 BPM. The sonified cueing track also included an embedded metronome. The same track was used for each of the three trials and for all participants. The piano arrangement of the folk tune was created to provide temporal, spatial, and force cues as outlined by C. P. Thaut (2014) in the *Handbook of Neurologic Music Therapy.* The sonified cue track met the principles of Patterned Sensory Enhancement (PSE) because it represented the spatial, temporal, and force elements of the arm reaching movement. The sonified cueing track included temporal cues including a salient quarter note beat and embedded metronome. The sonified cueing track included force cues by emphasizing the arm extension with accented chords. The track represented the spatial difference between the proximal and distal targets as the pitch range of the top note in the left hand on each beat. Additionally, the cueing track and matched the light style of contact with the target board with a staccato pattern. An example of a piano arrangement for sonified cueing is presented in Figure 3.

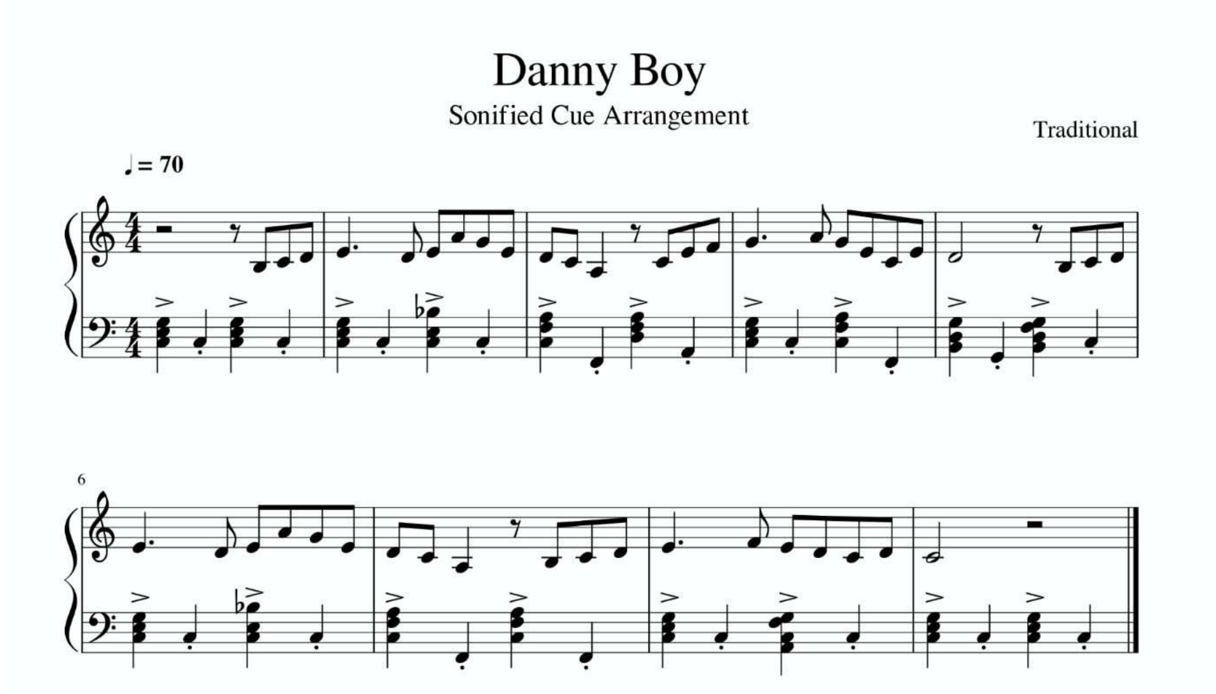

Figure 3. *Sonified Cue Piano Arrangement*
Note. The sonified cueing arrangement used in this study was of a different folk tune.

Study Procedure

All participants provided written informed consent on a form approved by the IRB of the affiliated institution. Participants were then seated in front of a table in the center of six motion capture cameras. The target board was placed on a table directly in front of the participant (see Figure 2). A research assistant affixed infrared-reflective markers at the shoulder, elbow, forearm, wrist, knuckle of the middle metacarpal, and phalangeal knuckle of the pointer finger of the participant's dominant upper extremity.

Each participant completed three 60-second trials of a repetitive arm reach task for each of three auditory cueing conditions including: 1) no auditory cueing, 2) rhythmic cueing at 70 beats per minute, and 3) sonified cueing at 70 beats per minute. To complete the repetitive reaching paradigm, a participant began with the index finger of their dominant hand on the proximal target of the target board. When instructed, the participant began moving their hand between the proximal and distal targets, tapping the target at each end. Participants repeated this movement until they were instructed to stop by a research assistant after 60 seconds. The coordinates of each infrared marker during each trial were recorded by the OptiTrack Infrared Motion Capture System. Participants took breaks of approximate 30 seconds between trials. During this time, research assistants saved files and provided verbal instructions.

Participants completed three trials in the no cueing condition first to ensure that it was self-paced and not influenced by the tempo of the auditory cues. A research assistant instructed the participant by stating "You are now going to tap the lower target and then the upper target, going back and forth at a comfortable pace until I say stop."

Participants completed three trials in both the rhythmic cueing and sonified cueing conditions. The three trials of each condition were consecutive, however the order of the conditions was randomized based on a pre-established randomization table. The purpose of randomization was to counterbalance any order effects that may be present. In the rhythmic cueing condition, a research assistant used the audio system to play the rhythmic cueing track. A research assistant instructed participants to match the pace of the metronome, saying "this time you will tap with the metronome to the best of your ability." The rhythmic cueing track began before the trail began and a research assistant instructed the participant to begin moving by saying “ready, go” in rhythm with the stimulus. Each participant completed three trials in the rhythmic cueing condition with a 30 second break between each trial.

In the sonified cueing condition, a research assistant used the audio system to play the sonified cueing track. A research assistant instructed participants to match the pace of the music, saying “this time you will tap with the music to the best of your ability.” The sonified cue track began with four preparatory beats, during which a research assistant provided the verbal cues “ready, go” in rhythm with the cueing track. Each participant completed three trials in the sonified cueing condition with a 30 second break between each trial.

Kinematic Analysis Parameters

Motion capture data from the wrist marker were processed using custom MatLab scripts (MathWorks, Natick, MA, USA) to determine two kinematic parameters for each trial–NJ and STI.

Normalized Jerk

Normalized jerk (NJ) is a quantitative indicator of movement smoothness (Teulings et al., 1997). In physics, jerk is the rate of change of acceleration and is calculated as the third derivative of position with respect to time (Gulde & Hermsdörfer, 2018). Jerk and movement smoothness are inversely correlated such that movements that are smooth have minimal jerk and movements that are not smooth have more jerk. Measures of jerk, therefore, can be used as quantitative indicators of the smoothness of human movements (Rohrer et al., 2002). Kinematics researchers often compute jerk as NJ in order to account for differences that may result from variation in path length or trial duration. A lower NJ value represents a smoother movement, which is considered optimal. Researchers calculate NJ by taking the square root of the quantity

(1)

of ½ of the integral of jerk (indicated as *j*) with respect to time multiplied by duration to the fifth over length squared (Teulings et al., 1997). See Equation 1 for the formula used to calculate NJ.

$$\mathrm{NJ} = \sqrt{\frac{1}{2}\int j^2 * \frac{duration^5}{length^2}} \qquad (1)$$

The author calculated the NJ of each trial using a custom MatLab script. The mean NJ of three trials of each cueing condition and participant were then calculated. These mean values were used in comparative statistical analyses.

Spatiotemporal Index

Spatiotemporal index (STI) is a single-value quantitative representation of the variability of the path of a movement (LaGasse, 2013; Smith et al., 2000). A lower STI value indicates less trajectory variability, which is considered an optimal kinematic pattern. A custom MatLab script was used to calculate STI. This MatLab script analyzed the first 10 movement segments in each trial (five extension and five flexion segments) at the wrist marker and created a model of an average repetition of the movement. The observed distance of the wrist maker from the modeled location was computed at 200 specified time points over the ten segments. The standard deviation of these differences in distance for flexion and extension segments was summed to produce the STI. For each participant, the mean STI for three trials of each cueing condition was calculated. These mean STI values were used in comparative statistical analyses.

Data Analysis

To answer R.Q. 1, a two-tailed independent samples *t*-test was run using Excel to compare NJ in the no cueing condition between the PD and CS groups. Similarly, to answer R.Q. 3, a two-tailed independent samples *t*-test was run using Excel to compare STI in the no cueing condition between the PD and CS groups.

To answer R.Q. 2 and R.Q. 4, a repeated measures analysis of variance (RMANOVA) was run using SPSS (IBM Inc., Armonk, NY, USA). Post-hoc tests were conducted using paired *t*-Tests to determine the source of any significance.

CHAPTER 4. RESULTS

Participant Characteristics

All participants in the college students (CS) group (*n* = 10; ages 19 to 21, *M* = 19.9, *SD* = 0.74) completed three trials in each of the three auditory cueing conditions. All data from these trials were included in statistical analyses. All participants in the Parkinson's disease (PD) group (*n* = 7; ages 68 to 82, *M* = 74.9, *SD* = 4.43) completed three trials in each of three cueing conditions. Demographic characteristics of participants in the PD group are presented in Table 1. Motion capture data from one trial (participant PD4, no cueing trial 1) were intermittently missing. As a result of these missing data, spatiotemporal index (STI) and normalized jerk (NJ) were not able to be computed for this trial. The STI and NJ values in the no cueing condition for participant PD4 are therefore reported and analyzed as the mean of the two trials for which motion capture data were fully recorded.

Table 1. *Parkinson's Disease Group Participant Demographics*

Participant ID	Age	Gender	Dominant Hand
PD1	72	Female	Right
PD2	68	Male	Right
PD3	74	Female	Right
PD4	76	Female	Left
PD5	77	Female	Right
PD6	75	Female	Right
PD7	82	Male	Left

Movement Smoothness

The kinematic parameter normalized jerk (NJ) was computed as an indicator of movement smoothness.

Group Differences With No Auditory Cueing

A two-tiled *t*-test for independent samples was run in Excel (Microsoft Corporation, Redmond, WA, USA) to examine the effects of group membership on NJ in the no cueing condition. The PD group demonstrated a larger mean NJ (M = 3185.39, SD = 3819.33) than the CS group (M = 1138.35, SD = 484.66); however, this difference was not statistically significant ($t(15) = 1.70$, $p = .11$, see Figure 4).

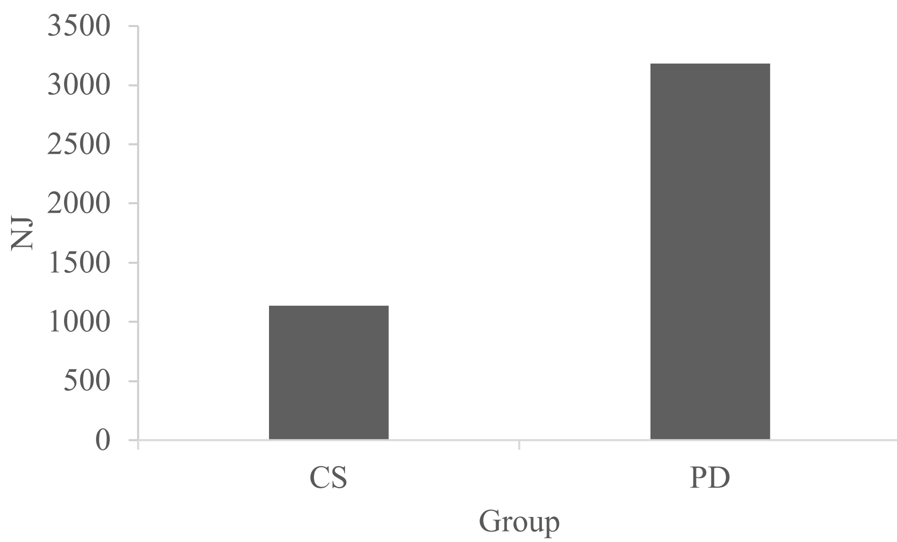

Figure 4. *Group Mean Normalized Jerk in the No Cueing Condition*
Note: NJ = normalized jerk; CS = college students; PD = Parkinson's disease

Effects of Group and Cueing Condition

Participant NJ values for each cueing condition are displayed in Table 2. Participant mean NJ values for the PD group are also represented in Figure 5. Figure 5 indicates that multiple participants in the PD group demonstrated higher NJ values in the rhythmic cueing condition than the no cueing condition, as well as lower NJ values in the sonified cueing condition than the no cueing condition. Group mean NJ values for each condition are displayed in Table 3 and Figure 6. Figure 6 indicates that the group mean NJ was greater for the PD group than the CS group in all three cueing conditions. Figure 6 also indicates that, for both groups, mean NJ values were greater in the rhythmic cueing condition than the no cueing and sonified cueing conditions.

Table 2. *Participant Normalized Jerk by Condition*

Participant	College Student Group			Participant	Parkinson's Disease Group		
	No Cueing	Rhythmic Cueing	Sonified Cueing		No Cueing	Rhythmic Cueing	Sonified Cueing
CS1	828.57	1216.21	1248.00	PD1	1821.52	1800.89	1933.93
CS2	2138.40	3485.66	2441.16	PD2	972.15	1109.17	1037.59
CS3	1228.87	1481.86	1161.56	PD3	4081.41	4771.21	4316.00
CS4	965.04	923.70	983.60	PD4	889.70*	892.23	882.01
CS5	611.20	616.27	677.14	PD5	11487.73	12039.97	10396.93
CS6	702.97	870.30	752.54	PD6	1864.24	1710.60	1716.16
CS7	1465.74	1780.63	1766.77	PD7	1180.99	1311.75	1046.03
CS8	1193.27	1232.87	1177.26				
CS9	676.56	683.76	698.76				
CS10	1572.94	1948.47	1695.16				

Note. *Mean in the no cueing condition for participant PD4 is represented as the mean of two trials due to missing data from the motion capture system.

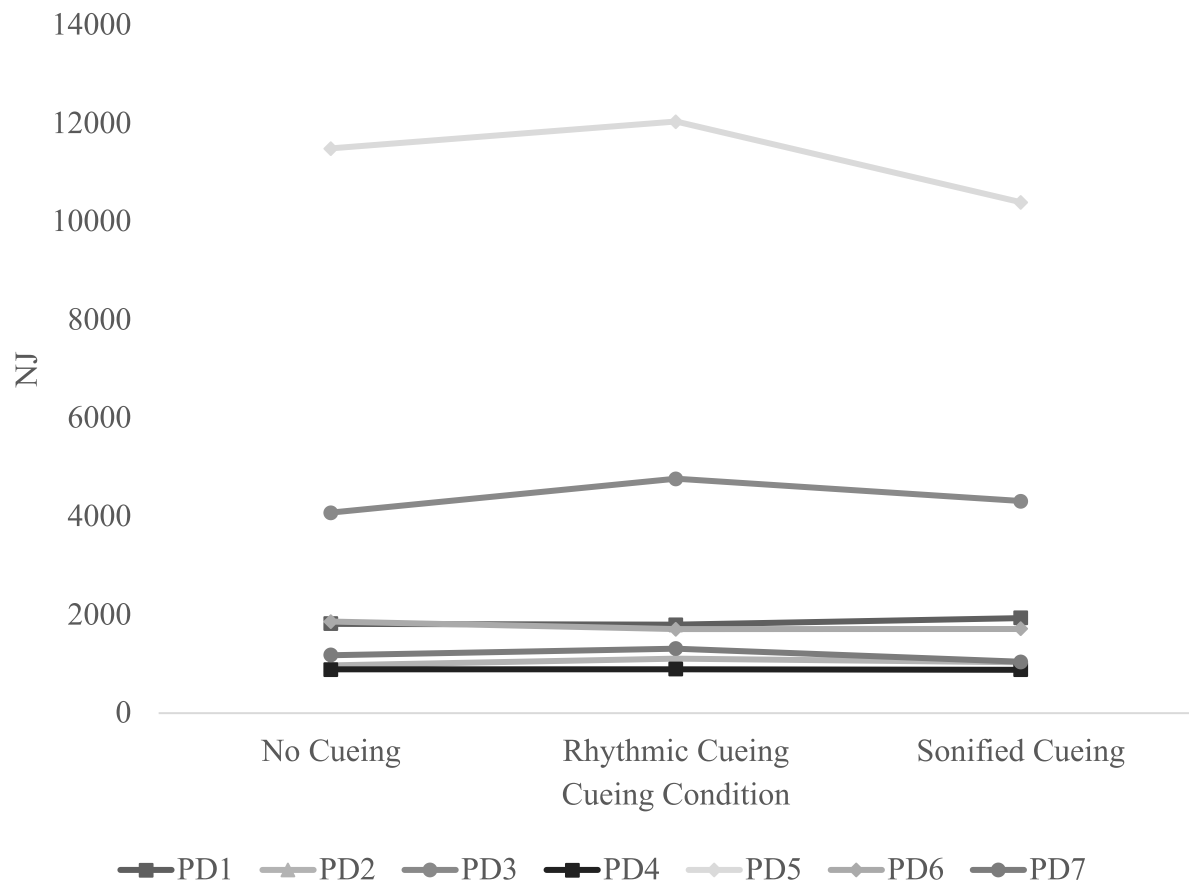

Figure 5. *PD Participant Normalized Jerk by Cueing Condition*
Note: NJ = normalized jerk; PD = Parkinson's disease

Table 3. *Normalized Jerk Descriptive Statistics by Group*

Group	*n*	No Cueing		Rhythmic Cueing		Sonified Cueing	
		M	*SD*	*M*	*SD*	*M*	*SD*
CS	10	1138.35	484.66	1423.97	849.38	1260.19	562.40
PD	7	3185.39	3536.01	3376.55	3738.49	3046.95	3193.09
All	17	1981.25	2584.71	2227.97	2738.91	1995.92	2336.70

Note: CS = college students; PD = Parkinson's disease

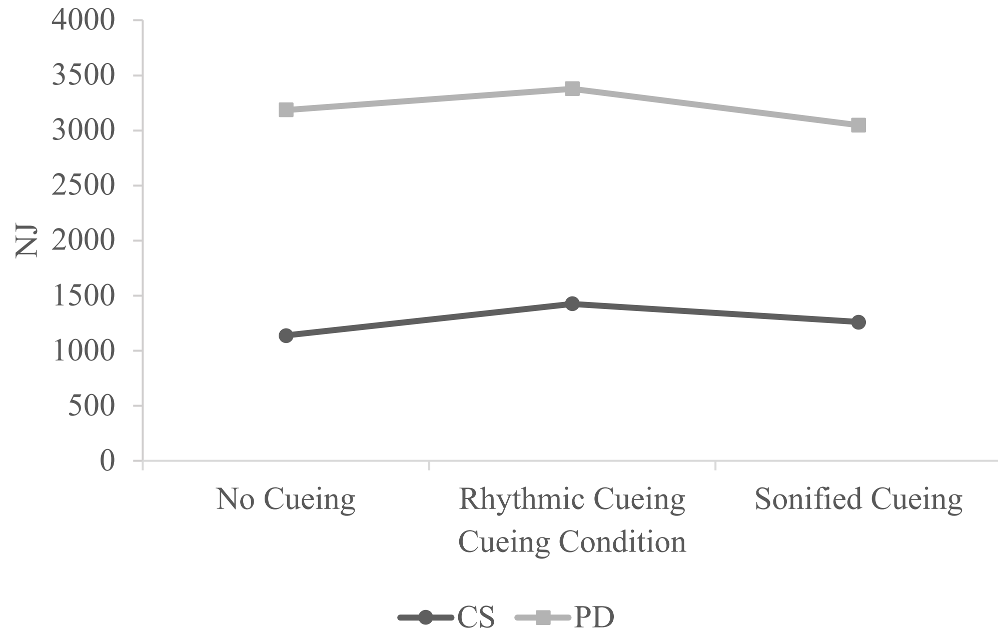

Figure 6. *Group Mean Normalized Jerk by Cueing Condition*
Note: NJ = normalized jerk; CS = college students; PD = Parkinson's disease

A 2x3 mixed design ANOVA was run in SPSS to examine the effects of group and cueing condition on NJ. This mixed design ANOVA indicated no significant cueing condition x time interaction effects ($F(2,30) = .96$, $p = .40$, partial $\eta 2 = .22$). The main effect of cueing condition was significant ($F(2,30) = 4.32$, $p = .02$, partial $\eta 2 = .22$). The main effect of group was not significant ($F(1,15) = 2.59$, $p = .12$, partial $\eta 2 = .15$). Post-hoc paired samples *t*-tests with a Bonferroni correction revealed a statistically significant difference in NJ between the no cueing ($M = 1981.25$, $SD = 2584.71$) and rhythmic cueing ($M = 2227.97$, $SD = 2738.91$) conditions ($t(16) = -2.80$, $p = .013$, Cohen's $d = .09$). No significant difference was found for other condition pairs (see Table 4).

Table 4. *Post-Hoc Paired t-Tests for Normalized Jerk Between Conditions*

Condition Pair		*df*	*t*	*p*	Cohen's *d*
Pair 1	No Cueing	16	-2.80	.013*	.09
	Rhythmic Cueing				
Pair 2	Rhythmic Cueing	16	2.09	.053	.09
	Sonified Cueing				
Pair 3	No Cueing	16	-.186	.854	.01
	Sonified Cueing				

Note: * indicates significance, 2-tailed at $\alpha < .016$. Post-hoc tests were conducted using data from all participants in the Parkinson's disease and college student groups. See table 3 for means and standard deviation normalized jerk for each cueing condition.

Movement Variance

Spatiotemporal index (STI) was computed as an indicator of movement path variance.

Group Differences With No Auditory Cueing

A two-tailed *t*-test for independent samples was run in Excel to examine the effects of group membership on STI in the no cueing condition. The PD group demonstrated a lower STI ($M = 1.12$, $SD = .50$) than the CS group ($M = 1.95$, $SD = 1.21$); however, this difference was not statistically significant ($t(15) = 1.70$, $p = 1.1$, see Figure 7).

Effects of Group and Condition

Participant STI values for each cueing condition are presented in Table 5. Individual STI values for participants in the PD group are additionally displayed in Figure 8. Figure 8 indicates that multiple participants in the PD group demonstrated greater STI in the no cueing condition, the rhythmic cueing condition, or both, than the sonified cueing condition. Group mean STI values for each cueing condition are presented in Table 5 and Figure 9. Figure 9 indicates that the CS group demonstrated higher STI values than the PD group in all three cueing conditions.

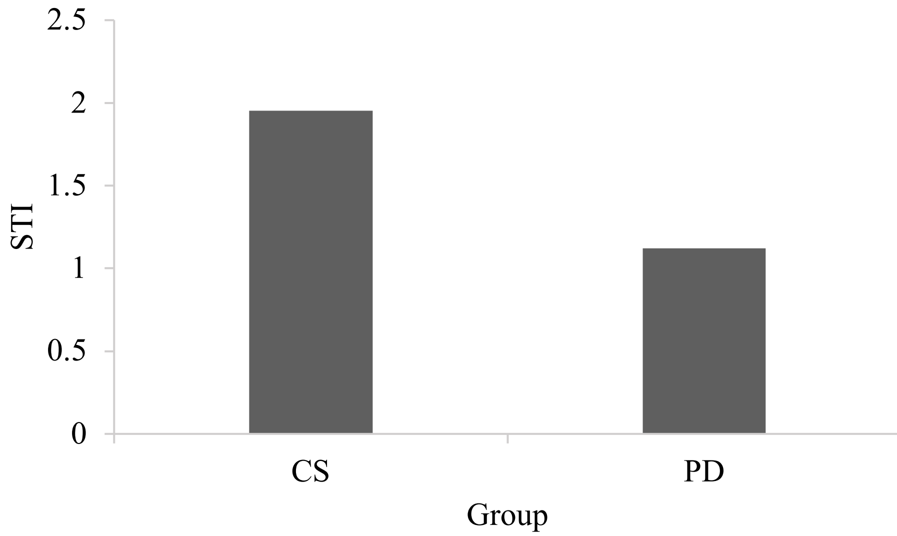

Figure 7. *Group Mean Spatiotemporal Index in the No Cueing Condition*
Note: STI = spatiotemporal index; CS = college students; PD = Parkinson's disease

Figure 9 also indicates that the STI for participants in the CS group was greater in the no cueing condition than the rhythmic cueing and sonified cueing conditions. Figure 9 further indicates that the STI for participants in the PD group was largest in the rhythmic cueing condition.

A 2x3 mixed design ANOVA was run in SPSS to examine the effects of group and cueing condition on STI. Mauchly's test of sphericity indicated that the assumption of sphericity was violated ($\chi 2(2) = 8.11$, $p = .017$) and therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .695$). With this correction, the mixed design ANOVA indicated a significant cueing condition x time interaction effect ($F(1.139,20.84) = 4.15$, $p = .04$, partial $\eta 2 = .22$). The main effect of condition was also significant ($F(1.139,20.84) = 4.28$, $p = .04$, partial $\eta 2 = .22$). The main effect of group was not significant.

Table 5. *Participant Spatiotemporal Index by Condition*

Participant	College Student Group			Participant	Parkinson's Disease Group		
	No Cueing	Rhythmic Cueing	Sonified Cueing		No Cueing	Rhythmic Cueing	Sonified Cueing
CS1	2.38	1.47	1.85	PD1	1.02	1.07	1.07
CS2	0.97	0.97	0.95	PD2	0.81	1.63	1.00
CS3	0.77	0.89	1.11	PD3	0.89	0.92	0.70
CS4	1.94	1.15	0.84	PD4	2.10*	1.65	1.16
CS5	1.01	1.19	1.03	PD5	0.56	0.75	0.82
CS6	1.78	1.10	1.25	PD6	1.42	1.18	0.97
CS7	4.73	2.97	2.18	PD7	1.06	1.55	1.10
CS8	1.55	0.97	0.77				
CS9	1.25	0.79	1.03				
CS10	3.14	1.48	2.06				

Note. *Mean in the no cueing condition for participant PD4 is represented as the mean of two trials due to missing data from the motion capture system. STI = spatiotemporal index; CS = college students; PD = Parkinson's disease

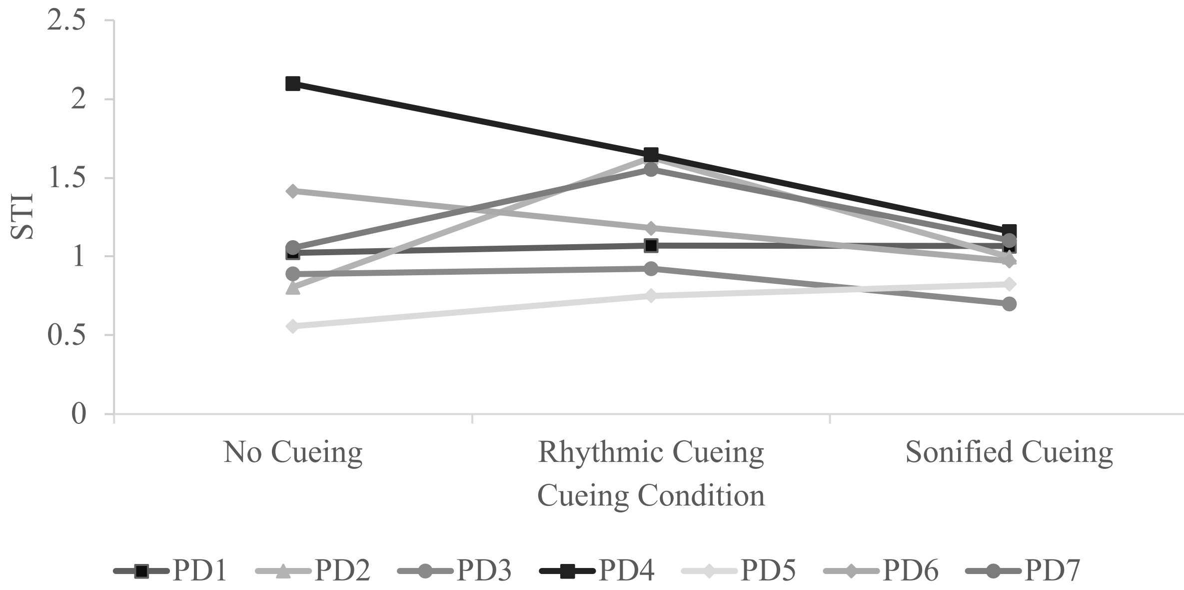

Figure 8. *PD Participant Spatiotemporal Index by Cueing Condition*
Note: STI = spatiotemporal index; CS = college students; PD = Parkinson's disease.($F(1,15)$ = 1.78, p = .20*,* partial $\eta 2$ = 1.06). Post-hoc paired samples *t*-tests with a Bonferroni correction (α = .016) revealed no statistically significant differences in STI between conditions (see Table 7).

Table 6. *Descriptive Statistics of Spatiotemporal Index by Group*

Group	*n*	No Cueing		Rhythmic Cueing		Sonified Cueing	
		M	*SD*	*M*	*SD*	*M*	*SD*
CS	10	1.95	1.21	1.30	0.63	1.31	0.52
PD	7	1.12	0.50	1.25	0.36	0.97	0.16
All	17	1.61	1.05	1.28	.52	1.17	.44

Note: CS = college students; PD = Parkinson's disease

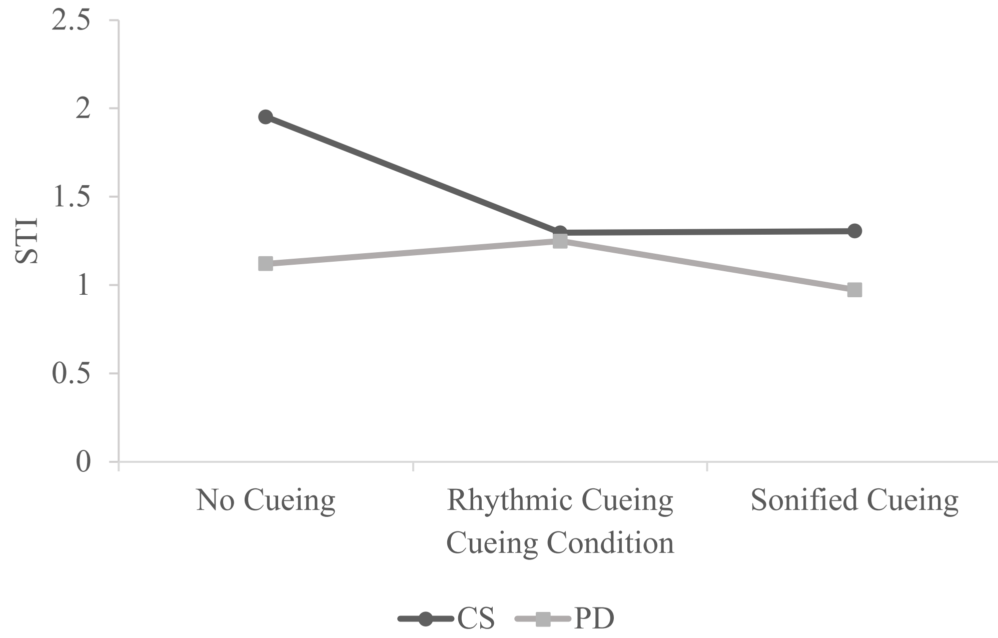

Figure 9. *Group Mean Spatiotemporal Index by Cueing Condition*
Note: STI = spatiotemporal index; CS = college students; PD = Parkinson's disease

Table 7. *Post-Hoc Paired t-Tests for Spatiotemporal Index Between Conditions*

Condition Pair		*df*	*t*	*p*	Cohen's *d*
Pair 1	No Cueing	16	1.97	.066	.40
	Rhythmic Cueing				
Pair 2	Rhythmic Cueing	16	1.23	.237	.09
	Sonified Cueing				
Pair 3	No Cueing	16	2.55	.022	.23
	Sonified Cueing				

Note: Post-hoc tests were conducted using data from all participants in the Parkinson's disease and college student groups. No paired tests reached the threshold of significance with the Bonferroni correction ($\alpha < .016$). See table 6 for means and standard deviations of spatiotemporal index for each cueing condition.

CHAPTER 5. DISCUSSION

The purpose of this study was to examine the effect of different types of auditory cueing on the smoothness and path variance of volitional arm movements in older adults with Parkinson's disease (PD). Examining the effect of cueing type on volitional arm movements may inform music therapist's practice in movement disorder rehabilitation, as well as provide insight into the conceptual and neurological working mechanisms that contribute to the effects of auditory cueing-based rehabilitation.

Group Differences in the No Cueing Condition

Between-group comparisons of movement smoothness using normalized jerk (NJ) and movement variance using spatiotemporal index (STI) were conducted to serve as baseline measures and to answer research questions 1 and 3 respectively. Participants completed three trials in the no cueing condition before completing trials with auditory cueing in order to prevent the cues from informing their movement pace and to prevent priming effects. Differences in kinematic parameters between the PD group and the comparison group of college students (CS) would therefore suggest that either normative aging or the pathology of PD contributed to these differences.

Movement Smoothness

With regard to R.Q. 1, the author hypothesized that there would be a significant difference in the NJ of trials with no cueing between the PD group and the CS group. The author conjectured that the motor symptoms of PD, namely tremors and bradykinesia, would contribute to the PD group demonstrating more variable movements, and therefore higher NJ values, than the CS group. Analysis revealed that the PD group demonstrated higher NJ (M = 3185.39, SD =

3819.33) than the CS group (*M* = 1138.35, *SD* = 484.66); however a two-tailed *t*-test revealed that this difference was not statistically significant. It is possible, however, that the large standard deviation in the PD group and the small sample size may have contributed to a type II error in the failure to reject the null hypothesis.

The absence of a statistically significant between-group difference in the no cueing condition is unexpected in the context of previous research, particularly considering the nonequivalence in age between the CS and PD groups. Alberts et al. (2000) compared the jerk of a reach and grasp task between older adults with PD and an age-matched comparison group. Alberts et al. (2000) found that the PD group demonstrated higher NJ values than the comparison group when reaching for both a large and small object and noted a significant group x target size interaction effect. These results suggest that there is a difference in NJ of reaching movements between older adults with and without PD.

The absence of between-group differences is also surprising because the expected differences may be exaggerated by the effects of normative ageing. The source of this anticipated confound is that normative aging contributes to changes in movement smoothness (Dixon et al., 2018). In order to examine the potential confound of age, participant age was entered as a covariate in one model of the RMANOVA for NJ. The inclusion of age as a variable did not impact the results, which suggests that age may not have been a confound in between-group comparisons in this sample. Regardless of the effects of the potential cofound of age, future researchers should control for this variable by recruiting an age-matched comparison group.

Another possible reason that no statistically significant between-group difference was found at baseline is that participants in the PD group demonstrated a wide range of NJ values in the no cueing condition (range 889.70 to 11487.73, see Table 2 and Figure 5). Combined with the small sample of the PD group (*n* = 7), the large standard deviation (*SD* = 3819.33) could mask significance that may be present in the populations from which convenience samples were drawn. The large standard deviation in the PD sample also suggests heterogeneity of the PD sample and the PD population more broadly. As PD is a progressive degenerative disorder, it may be hypothesized that movement smoothness decreases as the disease progresses, particularly after the point that tremors are present during volitional movements and not only when the affected limb is at rest (Pasquini et al., 2018). Measures of the progression of PD such as the Hoehn and Yahr (H&Y; 1967) scale may be analyzed as covariates to determine the effects of disease progression on movement smoothness. Hoehn and Yahr data, however, were not collected from the present sample.

Movement Variance

To answer R.Q. 3, a two-tailed *t*-test was run to compare the STI of trials in the no cueing condition between the PD and CS groups. The author hypothesized that there would be a significant difference between these groups. The *t*-test, however, revealed no significant difference between groups. Despite the difference not being statistically significant, the PD group demonstrated lower STI values (*M* = 1.12, *SD* = .50) than the CS group (*M* = 1.95, *SD* = 1.21) (see Table 6 and Figure 9). These results suggest that the PD group had less variability in the paths of volitional arm movements. The PD group demonstrating less path variability is unexpected because the author conjectured that the motor symptoms of PD may contribute to more variable movement paths.

One possible explanation for lower STI values in the PD group is that participants with PD may have used previously established cognitive or motor strategies to compensate for motor declines and complete the arm reaching task with little path variance. If participants applied the same strategies to each of repetition of the task, the movement paths of each repetition may have been minimized. Such strategies may have included sub-vocalized auditory cueing (Harrison et al., 2019), increased trunk movement (Dounskaia et al., 2009), or increased attention to a goal-directed movement (David et al., 2012). It should also be noted that STI is a measure of path variance across repetitions within a trial and does not represent variance between trials. Visual comparison of the motor paths is an alternate technique for evaluating the effects of group and cueing condition on movement performance; however, visual inspection techniques are less precise than quantitative measure such as STI and were not utilized in the present study.

Effects of Cueing Type and Group

Movement Smoothness

A repeated measures analysis of variance (RMANOVA) and post-hoc *t*-tests were run to answer R.Q. 2 and revealed that, for the full participant pool, movement smoothness was poorer in the rhythmic cueing condition (NJ $M = 2227.97$, $SD = 2738.91$) than the no cueing condition ($M = 1981.25$, $SD = 2584.71$). Significantly higher NJ in the rhythmic cueing condition than the no cueing condition is unexpected, considering the clinical use of rhythmic cueing in upper motor rehabilitation (Thaut et al., 2002). Higher NJ in the rhythmic cueing condition, as compared to the no cueing condition, may suggest that the neurological activations involved in rhythmic entrainment may contribute to undesirable changes in the motor patterns of volitional movements. This interpretation, however, should be considered cautiously due to the small sample size. Furthermore, the effect size of the difference between the rhythmic cueing and no cueing conditions is small (Cohen's $d = .09$). This small effect size indicates that the magnitude of difference in movement smoothness between the conditions was small. Future research is warranted to examine the possible effect of rhythmic cueing on movement smoothness and evaluate the neurological mechanisms that may contribute to this effect.

One participant in the PD group (PD 5) exhibited NJ values that were greater than two standard deviations larger than the sample means, therefore indicating that this participant may have been an outlier. Therefore, a RMANOVA was run with participant PD5 excluded. This model did not change which effects were significant. The results of less modified and more conservative tests that include participant PD 5 were presented in this study.

The present study was exploratory and likely had low statistical power, and therefore had a high likelihood of type II error. Although conclusions cannot be drawn based on the present data, additional auditory cueing research is warranted and future researchers may consider trends from the present study to formulate hypotheses for studies with larger samples. One trend that future researchers may consider exploring is that NJ was greater in the rhythmic cueing condition than the no cueing and sonified cueing conditions for both the PD and CS groups (see Figure 6). This trend of poorer movement performance in the rhythmic cueing condition also appears at the individual level. Five of the seven participants in the PD group had their highest NJ in the rhythmic cueing condition (see Table 2 and Figure 5). Future researchers may consider evaluating the effects of rhythmic cueing on volitional upper extremity movement in older adults with PD in order to assess the effects of rhythmic entrainment and other rhythm-dependent working mechanisms on non-intrinsically rhythmic movements.

Another trend that future researchers may consider exploring is that the PD group had their lowest mean NJ in the sonified cueing condition (see Table 3). Furthermore, five out of the seven participants in the PD group had their individual lowest NJ in the sonified cuing condition (see Table 2). Although these findings were not statistically significant, the trend of better movement smoothness in the sonified cueing condition, compared to the no cueing and rhythmic cueing conditions, warrants further research to examine the effects of individual elements of auditory cues on motor performance. Future research may also examine potential differences in neurological responses to various musical elements and auditory cueing techniques. Understanding the neurological and motor responses to particular elements of music may help music therapists optimize motor rehabilitation techniques for various types of movements with older adults with PD.

Movement Variance

A RMANOVA of STI data was run to examine the effects of group and cueing condition on movement path variance and answer R.Q. 4. After taking the Greenhouse-Geisser correction, the RMANOVA revealed a significant main effect of cueing condition. Post-hoc paired *t*-tests with the Bonferroni correction, however, did not find any significant differences between cueing conditions. The comparison between the no cueing (M = 1.61, SD = 1.05) and sonified cueing (M = 1.17, SD = .04) conditions, however, approached significance (p = *.022,* α = .016). The magnitude of this trend of difference, however, was small (Cohen's d = .23) and therefore may not be clinically meaningful to music therapists. Considering the exploratory nature of the present study, further research is warranted to more thoroughly evaluate the potential differential effects of rhythmic cueing and sonified cueing on movement path variance.

The comparison of STI between the no cueing and rhythmic cueing conditions had the greatest effect size of any paired condition test (Cohen's d = .40). Cohen's d = .40, however, is still considered a small effect size and the difference in STI between the no cueing and rhythmic cueing conditions was not statistically significant. The greater effect size than other comparisons within the present sample, as well as documented differences in spatial and temporal movement parameters of an arm movement in response to rhythmic cueing in stroke survivors (Thaut et al., 2002), warrants further examination of the effects of rhythm on volitional movements in older adults with PD.

The RMANOVA indicated a significant cueing condition x group interaction effect. This interaction effect suggests that different cueing conditions may have affected the STI of participants in the PD and CS groups differently. The PD group had higher STI in the rhythmic cueing condition than the no cueing condition, while the CS group demonstrated the opposite trend (see Figure 9). The convergence of group STI values from the no cueing to the rhythmic cueing condition may have contributed to the significant interaction effect. Additional research is necessary to examine the factors that may contribute to this convergence.

The PD group had a higher mean STI in the rhythmic cueing condition than the no cueing condition and four of the seven participants in the PD group had their highest STI in the rhythmic cueing condition (see Figure 8). These findings are similar to trends in the movement smoothness results. Future researchers may further examine possible differences in responses to rhythmic and musical cueing in order to evaluate the role of rhythm-dependent and non-rhythm-dependent working mechanisms on motor function.

Implications of Results for Working Mechanisms

Rhythm-Dependent Working Mechanisms

Theories related to the proposed neurological working mechanisms of entrainment, priming, and motor plan monitoring suggest that the effects of these mechanisms are dependent on neurological responses to rhythmic elements of auditory cues. Both the rhythmic and sonified cues in the present study contained salient rhythmic temporal information. Therefore, if rhythm-dependent working mechanisms were the primary working mechanisms in auditory cueing of volitional arm movements, it would be expected that the motor outcomes of the rhythmic and sonified cueing conditions would be the same (Nombela et al., 2013; Pecenka et al., 2013; Thaut et al., 2015). A trend of less smooth and more variable movement in the rhythmic cueing condition than the sonified cueing condition warrants future research to determine if entrainment, priming, or motor plan monitoring are the primary working mechanisms of auditory cueing of volitional movements.

Entrainment, priming, and motor plan monitoring are distinct and not mutually exclusive—however, due to methodological decisions in the present study, it is difficult to further differentiate the potential effects of these working mechanisms. Furthermore, it is difficult to evaluate the potential role of long-term priming (Braun Janzen et al., 2019) and priming due to neurological oscillation suppression (Crasta et al., 2018) based on the present data. Additional research is warranted to examine the potentially independent roles of entrainment, priming, and motor plan monitoring and perhaps establish an integrated model of the effects of various neurological phenomena that may affect volitional movement performance.

One explanation for why evidence of rhythm-based working mechanisms were not observably active in the present study is that these working mechanisms were proposed based on observations of gait training. Gait is neurologically distinct from upper extremity reaching because gait is regulated by central pattern generators, whereas each repetition of an upper extremity reaching movement is independently volitional. The documented effects of rhythmic cueing on gait may not be transferable to volitional upper extremity movements because the activation and entrainment of central pattern generators, which is the proposed neurological working mechanism of cueing-based gait rehabilitation, may not affect volitional movements (Devlin et al., 2019; Thaut & Rice, 2014). Working mechanisms that are not strictly rhythm-dependent may therefore be active in order for musical cues to contribute to improved performance on a volitional movement task.

A mechanism that may contribute to the effects of auditory cues on volitional movements is cognitive processing of rhythmic and musical cues. This cognitive processing may occur as part of a neurological sequence in which cues are detected in auditory brain regions, processed in the frontal lobe executive networks, and then conveyed to the premotor and supplementary motor areas where they are used to create and execute motor plans. Braunlich et al. (2019) supported the neurological validity of an auditory-frontal-motor compensatory pathway by demonstrating sequential neurological connectivity between each of the aforementioned brain areas. Exploratory results of the current study warrant further exploration of the frontal lobe compensatory hypothesis because participants tended to have better movement parameters in the sonified cueing condition than the rhythmic cueing condition. Within the frontal lobe compensatory framework, better performance in the sonified cueing condition may suggest that the frontal lobe executive networks are able to process and relay information from sonified cues more optimally than rhythmic cues.

The frontal lobe compensatory mechanism hypothesis may explain the observed differences in response to different cueing conditions and may also account for changes that occur as a result of disease progression. If the frontal lobe compensatory hypothesis is true, older adults with PD may regulate motor function using the frontal lobes, rather than the basal nuclei. The frontal lobes would therefore need to appropriately process sensory or other neurological input in order to effectively regulate activity in the pre-motor and supplementary motor areas. This input to the frontal lobes may include information from the auditory cortex. The observed differences between the rhythmic and sonified cueing conditions in the present study suggest that sonified cueing, which included the melody of a well-known folk song, may have engaged the frontal lobes more optimally than did rhythmic cueing. Older adults with PD who are capable of effectively processing auditory cues may interpret musical elements in addition to rhythm as providing information about the target movement. Additional research would be needed to identify what musical components; such as harmony, melody, dynamics, accents, or the participant's familiarity with the music; may contribute to neurological and motor responses to musical cueing.

As the cognitive symptoms of PD progress, older adults may have difficulty processing complex musical stimuli (Bellinger et al., 2017). In these later stages of disease progression, comparatively simple cues, such as the rhythmic cues used in the present study, may be the optimal input to the frontal lobes because the brain may be able to process rhythmic cues as representing the timing of the movement without being overwhelmed by other complex musical elements. Examining the covariation of indicators of the progression of PD with motor performance between auditory cueing conditions may suggest changes in cognitive processing of auditory cues as PD progresses. A relationship between motor performance, cognitive symptoms of PD, and cueing type may support the frontal lobe compensatory mechanism hypothesis because such findings may provide evidence for the involvement of frontal lobe executive networks in auditory cueing of volitional movements. Further research is warranted to explore the validity of the frontal lobe compensatory mechanism hypothesis.

Engagement and Relational Mechanisms

Researchers including Street (2012), Cameron et al. (2016), and Mainka (2015) have suggested that a strong therapeutic relationship and a music therapy client's engagement with the music may contribute to better motor rehabilitation outcomes. Data in this study, however, were collected in a single session by trained research assistants, therefore controlling the potential effects of the therapeutic relationship on kinematic outcomes. Future researchers, however, may consider evaluating the therapeutic relationship as an independent variable in auditory cueing research.

Cameron et al. (2016) suggested that the function of musical engagement may be to increase clients' attention to rhythmic elements of the cueing stimulus, thereby further improving the effects of rhythm-based working mechanisms. Clients' familiarity with musical cues, particularly cues that include elements of well-known pieces of music, may also affect engagement with the music. Future research would be needed to evaluate the effects of musical characteristics of auditory cues on the accuracy of period matching among older adults with different stages of PD.

Implications for Music Therapy Practice

The results of this study are exploratory and should be interpreted with caution by music therapy clinicians. These preliminary results suggest that musical cueing may contribute to more optimal kinematic performance than rhythmic cueing among older adults with PD (see Figure 6 and Figure 9). Small effect sizes and a lack of statistical significance, however, suggest that the trends of differences between cueing conditions may not be clinically significant. Additionally, the brain may respond differently to different musical characteristics (Izbicki et al., 2020). Therefore, music therapists should consider musical elements in addition to rhythm when planning therapeutic musical experiences to address motor goals with older adults with PD. Selecting the characteristics of auditory cues is one of numerous considerations music therapists make in applying the principles of evidence-based practice. Clinicians should consider client preferences, professional expertise, and interpersonal factors when planning and implementing therapeutic musical experiences.

Limitations

The present study had numerous limitations. First, the sample in this study was small. Statistical power was therefore low, leaving a high likelihood of type II error. Significant differences may exist within and between the populations of college students and older adults with PD that were not captured in this sample. Another limitation of the sample in this study was the lack of a comparison group that was age-matched to the PD group. The lack of an age-matched comparison group means that the between-group differences found in the study, albeit not statistically significant, cannot be attributed to PD because age confounded all of the between-group comparisons.

Another limitation of this study is the absence of measures representing the stage of disease progression, such as H&Y scores, for participants with PD. Despite the small sample size, H&Y scores would have allowed for preliminary analysis of disease progression as a covariate in between-condition comparisons. This comparison may have suggested whether older adults in the later stages of PD respond differently to auditory cues than those who are in the earlier stages of disease progression. For example, if auditory-motor responses are mediated by the frontal lobes and optimized by the level of cognitive load, older adults with PD may have poorer motor responses to sonified cues after the disease progresses to the extent that sonified cues become difficult for older adults to cognitively process. Considerable further research with a larger sample would be needed to evaluate this hypothesis.

The present study is also limited because only motion capture data from the wrist marker were analyzed. The wrist marker was selected because earlier PD motion capture research that used a similar reaching movement analyzed the wrist marker (Bertram et al., 2005). The wrist marker may, however, be less sensitive to changes in movement smoothness than the knuckle or finger because the wrist remains relatively stationary during a rotational tremor, as compared to the finger. Motion capture data from markers on the hand may therefore be more sensitive to kinematic effects of the motor symptoms of PD. Future auditory cueing researchers using motion capture techniques may consider evaluating kinematic parameters from multiple markers in order to more thoroughly assess the effects of cueing on the motor symptoms of PD.

Finally, the generalizability of findings from this study are limited because the movement task and kinematic parameters used for analysis do not necessarily reflect the functional abilities of older adults with PD. Although poor movement smoothness and high movement path variance have been associated with functional disabilities, results from the present study cannot be interpreted as representing the effects of auditory cueing on functional skills such as activities of daily living.

Future Directions

Future researchers may consider replicating the present study with a larger sample size and a comparison group of older adults with no neurological disorders in order to improve statistical power and eliminate the confound of age. Researchers who replicate this study should also collect data related to disease progression for participants in the PD group and analyze these data as a covariate in between-condition comparisons.

Researchers may consider using electrophysiological data such as electroencephalography (EEG) and electromyography (EMG), in addition to motion capture, to examine the effects of auditory cueing on neurological motor control and movement parameters. Combining these techniques may help researchers understand the timing of neurological and physical events and may therefore lead to a better understanding of the neurological pathways involved in the motor response to auditory cueing. Electrophysiological research may also contribute to a better understanding of the brain's response to distinct musical characteristics (Stegemöller et al., 2018), which may inform the creation of optimal auditory movement cues.

Future research is warranted to specifically examine the role of cognition and frontal lobe executive activity in auditory-motor responses. Such studies may involve both EEG and motion capture in order to compare the effects of frontal lobe activity in various cuing conditions to the resultant movement parameters. If there is a pattern of neurological activation, rather than a combination of musical factors, that is associated with improved upper extremity motor function, music therapists may be able to optimize cueing-based therapeutic musical experiences for older adults with different neurological profiles.

Conclusion

The present study indicated that rhythmic cueing did not contribute to better kinematic performance of volitional movements for older adult participants with PD. The present study also indicated that participants demonstrated smoother and less variable movements in response to sonified musical cues; however this trend did not reach the threshold of statistical significance. Future research is warranted to examine the effects of auditory cueing on kinematic parameters and long-term rehabilitation of volitional movements of older adults with PD. Meanwhile, music therapists may use musical cues when working with older adults with PD in order to optimize the effects of relational, engagement, and proposed physiological working mechanisms within the therapeutic process. The present study adds to the music therapy literature by formalizing and presenting exploratory evidence for the frontal lobe compensatory mechanism hypothesis, which may account for differences in motor responses to different types of auditory cueing.

REFERENCES

Aboelnasr, E. A., Hegazy, F. A., & Altalway, H. A. (2017). Kinematic characteristics of reaching in children with hemiplegic cerebral palsy: A comparative study. *Brain Injury, 31*(1), 83-89. https://doi.org/10.1080/02699052.2016.1210230

Alberts, J. L., Saling, M., Adler, C. H., & Stelmach, G. E. (2000). Disruptions in the reach-to-grasp actions of Parkinson's patients. *Experimantal Brain Research, 134*(3), 353-362. https://doi.org/10.1007/s002210000468

American Music Therapy Association (AMTA). (n.d.). *What is music therapy*. https://www.musictherapy.org/about/musictherapy/

Ashoori, A., Eagleman, D. M., & Jankovic, J. (2015). Effects of auditory rhythm and music on gait disturbances in Parkinson's disease. *Frontiers in Neurology, 6*(234). https://doi.org/10.3389/fneur.2015.00234

Batson, G., Hugenschmidt, C. E., & Soriano, C. T. (2016). Verbal auditory cueing of improvisational dance: A proposed method for training agency in Parkinson's disease. *Frontiers in Neurology, 7*, 15. https://doi.org/10.3389/fneur.2016.00015

Bellinger, D., Altenmüller, E., & Volkmann, J. (2017). Perception of time in music in patients with Parkinson's disease–The processing of musical syntax compensates for rhythmic deficits. *Frontiers in Neuroscience, 11*, 68. https://www.frontiersin.org/article/10.3389/fnins.2017.00068

Bertram, C. P., Lemay, M., & Stelmach, G. E. (2005). The effect of Parkinson's disease on the control of multi-segmental coordination. *Brain and Cognition, 57*(1), 16-20. https://doi.org/10.1016/j.bandc.2004.08.014

Blandy, L. M., Beevers, W. A., Fitzmaurice, K., & Morris, M. E. (2015). Therapeutic Argentine Tango dancing for people with mild Parkinson's disease: A feasibility study. *Frontiers in Neurology, 6*. https://doi.org/10.3389/fneur.2015.00122

Bologna, M., Paparella, G., Fasano, A., Hallett, M., & Berardelli, A. (2020). Evolving concepts on bradykinesia. *Brain, 143*(3), 727-750. https://doi.org/10.1093/brain/awz344

Braun Janzen, T., Haase, M., & Thaut, M. H. (2019). Rhythmic priming across effector systems: A randomized controlled trial with Parkinson's disease patients. *Human Movement Science, 64*, 355-365. https://doi.org/10.1016/j.humov.2019.03.001

Braunlich, K., Seger, C. A., Jentink, K. G., Buard, I., Kluger, B. M., & Thaut, M. H. (2019). Rhythmic auditory cues shape neural network recruitment in Parkinson's disease during repetitive motor behavior. *European Journal of Neuroscience, 49*(6), 849-858. https://doi.org/10.1111/ejn.14227

Cameron, D. J., Pickett, K. A., Earhart, G. M., & Grahn, J. A. (2016). The effect of dopaminergic medication on beat-based auditory timing in Parkinson's disease. *Frontiers in Neurology, 7*, 19. https://doi.org/10.3389/fneur.2016.00019

Cheung, C., Bhimani, R., Wyman, J. F., Konczak, J., Zhang, L., Mishra, U., Terluk, M., Kartha, R. V., & Tuite, P. (2018). Effects of yoga on oxidative stress, motor function, and non-motor symptoms in Parkinson's disease: a pilot randomized controlled trial. *Pilot and Feasibility Studies, 4*(1), 162. https://doi.org/10.1186/s40814-018-0355-8

Cilia, R., Cereda, E., Akpalu, A., Sarfo, F. S., Cham, M., Laryea, R., Obese, V., Oppon, K., Del Sorbo, F., Bonvegna, S., Zecchinelli, A. L., & Pezzoli, G. (2020). Natural history of motor symptoms in Parkinson's disease and the long-duration response to levodopa. *Brain, 143*(8), 2490-2501. https://doi.org/10.1093/brain/awaa181

Clark, I. N., Baker, F., & Taylor, N. F. (2012). The effects of live Patterned Sensory Enhancement on group exercise participation and mood in older adults in rehabilitation. *Journal of Music Therapy, 49*(2), 180-204. https://doi.org/10.1093/jmt/49.2.180

Crasta, J. E., Thaut, M. H., Anderson, C. W., Davies, P. L., & Gavin, W. J. (2018). Auditory priming improves neural synchronization in auditory-motor entrainment. *Neuropsychologia, 117*, 102-112. https://doi.org/10.1016/j.neuropsychologia.2018.05.017

David, F. J., Rafferty, M. R., Robichaud, J. A., Prodoehl, J., Kohrt, W. M., Vaillancourt, D. E., & Corcos, D. M. (2012). Progressive resistance exercise and Parkinson's disease: A review of potential mechanisms. *Parkinson's Disease, 2012*, 1-10. https://doi.org/10.1155/2012/124527

del Olmo, M. F., Arias, P., Furio, M. C., Pozo, M. A., & Cudeiro, J. (2006). Evaluation of the effect of training using auditory stimulation on rhythmic movement in Parkinsonian patients—a combined motor and [18F]-FDG PET study. *Parkinsonism & Related Disorders, 12*(3), 155-164. https://doi.org/10.1016/j.parkreldis.2005.11.002

del Olmo, M. F., & Cudeiro, J. (2005). Temporal variability of gait in Parkinson disease: Effectsof a rehabilitation programme based on rhythmic sound cues. *Parkinsonism & Related Disorders, 11*(1), 25-33. https://doi.org/10.1016/j.parkreldis.2004.09.002

Devlin, K., Alshaikh, J. T., & Pantelyat, A. (2019). Music therapy and music-based interventions for movement disorders. *Current Neurology and Neuroscience Reports, 19*(11), 83. https://doi.org/10.1007/s11910-019-1005-0

Dixon, P. C., Stirling, L., Xu, X., Chang, C. C., Dennerlein, J. T., & Schiffman, J. M. (2018). Aging may negatively impact movement smoothness during stair negotiation. *Human Movement Science, 60*, 78-86. https://doi.org/10.1016/j.humov.2018.05.008

Dounskaia, N., Fradet, L., Lee, G., Leis, B. C., & Adler, C. H. (2009). Submovements during pointing movements in Parkinson's disease. *Experimental Brain Research, 193*(4), 529-544. https://doi.org/10.1007/s00221-008-1656-6

Drucker, J. H., Sathian, K., Crosson, B., Krishnamurthy, V., McGregor, K. M., Bozzorg, A., Gopinath, K., Krishnamurthy, L. C., Wolf, S. L., Hart, A. R., Evatt, M., Corcos, D. M., & Hackney, M. E. (2019). Internally guided lower limb movement recruits compensatory cerebellar activity in people with Parkinson's disease. *Frontiers in Neurology, 10*, 537. https://doi.org/10.3389/fneur.2019.00537

Feng, Y.-S., Yang, S.-D., Tan, Z.-X., Wang, M.-M., Xing, Y., Dong, F., & Zhang, F. (2020). The benefits and mechanisms of exercise training for Parkinson's disease. *Life Sciences, 245*, 117345. https://doi.org/10.1016/j.lfs.2020.117345

Ford, M. P., Malone, L. A., Nyikos, I., Yelisetty, R., & Bickel, C. S. (2010). Gait training with progressive external auditory cueing in persons with Parkinson's disease. *Archives of Physical Medicine and Rehabilitation, 91*(8), 1255-1261. https://doi.org/10.1016/j.apmr.2010.04.012

Fukui, T., Sano, M., Tanaka, A., Suzuki, M., Kim, S., Agarie, H., Fukatsu, R., Nishimaki, K., Nakajima, Y., & Wada, M. (2018). Older adolescents and young adults with Autism Spectrum Disorder have difficulty chaining motor acts when performing prehension movements compared to typically developing peers. *Frontiers in Human Neuroscience, 12*(430). https://doi.org/10.3389/fnhum.2018.00430

García-Casares, N., Martín-Colom, J. E., & García-Arnés, J. A. (2018). Music therapy in Parkinson's disease. *Journal of the American Medical Directors Association, 19*(12), 1054-1062. https://doi.org/10.1016/j.jamda.2018.09.025

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience, 19*(5), 893-906. https://doi.org/10.1162/jocn.2007.19.5.893

Grahn, J. A., & Watson, S. L. (2013). Perspectives on rhythm processing in motor regions of the brain. *Music Therapy Perspectives, 31*(1), 25-30. https://doi.org/10.1093/mtp/31.1.25

Gulde, P., & Hermsdörfer, J. (2018). Smoothness metrics in complex movement tasks. *Frontiers in Neurology, 9*(615). https://doi.org/10.3389/fneur.2018.00615

Gutman, S. A. (2017). Motor functions and dysfunctions of the central nervous system: Cortex, basal ganglia, cerebellum. In S. A. Gutman (Ed.), *Quick reference neuroscience for rehabilitation professionals: The essential neurologic principles underlying rehabilitation practice* (3rd ed., pp. 256-273). SLACK Incorporated.

Hallett, M., & Khoshbin, S. (1980). A physiological mechanism of bradykinesia. *Brain: A Journal of Neurology, 103*(2), 301-314. https://doi.org/10.1093/brain/103.2.301

Harrison, E. C., Horin, A. P., & Earhart, G. M. (2019). Mental singing reduces gait variability more than music listening for healthy older adults and people with Parkinson disease. *Journal of Neurologic Physical Therapy, 43*(4). https://doi.org/10.1097/NPT.0000000000000288

Hoehn, M. M., & Yahr, M. D. (1967). Parkinsonism: Onset, progression, and mortality. *Neurology, 17*(5), 427-442. https://doi.org/10.1212/WNL.17.5.427

Isenberg, C., & Conrad, B. (1994). Kinematic properties of slow arm movements in Parkinson's disease. *Journal of Neurology, 241*(5), 323-330. https://doi.org/10.1007/BF00868441

Izbicki, P., Zaman, A., & Stegemöller, E. L. (2020). Music form but not music experience modulates motor cortical activity in response to novel music. *Frontiers in Human Neuroscience, 14*(127). https://doi.org/10.3389/fnhum.2020.00127

Kang, S., Shin, J.-H., Kim, I. Y., Lee, J., Lee, J.-Y., & Jeong, E. (2020). Patterns of enhancement in paretic shoulder kinematics after stroke with musical cueing. *Scientific Reports, 10*(1), 18109. https://doi.org/10.1038/s41598-020-75143-0

Kim, H.-D., Jae, H. D., & Jeong, J. H. (2014). Tai chi exercise can improve the obstacle negotiating ability of people with Parkinson's disease: A preliminary study. *Journal of Physical Therapy Science, 26*(7), 1025-1030. https://doi.org/10.1589/jpts.26.1025

Knierim, J. (2020). Basal ganglia. In *Neuroscience online: An electronic textbook for the neurosciences* (Vol. 3). University of Texas UT Health. https://nba.uth.tmc.edu/neuroscience/s3/chapter04.html

Konieczny, M., Paweł, P., & Monika, B. (2020). Kinematic analysis of upper extremity movement in stroke patients as a rehabilitation supporting tool. *Research Square*. https://doi.org/10.21203/rs.3.rs-39559/v1

LaGasse, A. B. (2013). Influence of an external rhythm on oral motor control in children and adults. *Journal of Music Therapy, 50*(1), 6-24. https://doi.org/10.1093/jmt/50.1.6

Lindaman, K., & Abiru, M. (2013). The use of rhythmic auditory stimulation for gait disturbance in patients with neurologic disorders. *Music Therapy Perspectives, 31*(1), 35-39. https://doi.org/10.1093/mtp/31.1.35

Mainka, S. (2015). Music stimulates muscles, mind, and feelings in one go. *Frontiers in Psychology, 6*, 1547. https://doi.org/10.3389/fpsyg.2015.01547

Marras, C., Beck, J. C., Bower, J. H., Roberts, E., Ritz, B., Ross, G. W., Abbott, R. D., Savica, R., Van Den Eeden, S. K., Willis, A. W., Tanner, C. M., & on behalf of the Parkinson's Foundation, P. G. (2018). Prevalence of Parkinson's disease across North America. *npj Parkinson's Disease, 4*(1), 21. https://doi.org/10.1038/s41531-018-0058-0

Morris, M. E., Ellis, T. D., Jazayeri, D., Heng, H., Thomson, A., Balasundaram, A. P., & Slade, S. C. (2019). Boxing for Parkinson's disease: Has implementation accelerated beyond current evidence? *Frontiers in Neurology, 10*, 1222. https://doi.org/10.3389/fneur.2019.01222

Mündermann, L., Corazza, S., & Andriacchi, T. P. (2006). The evolution of methods for the capture of human movement leading to markerless motion capture for biomechanical applications. *Journal of neuroengineering and rehabilitation, 3*, 1-11. https://doi.org/10.1186/1743-0003-3-6

Mure, H., Hirano, S., Tang, C. C., Isaias, I. U., Antonini, A., Ma, Y., Dhawan, V., & Eidelberg, D. (2011). Parkinson's disease tremor-related metabolic network: Characterization, progression, and treatment effects. *NeuroImage, 54*(2), 1244-1253. https://doi.org/10.1016/j.neuroimage.2010.09.028

Nieuwboer, A., Kwakkel, G., Rochester, L., Jones, D., van Wegen, E., Willems, A. M., Chavret, F., Hetherington, V., Baker, K., & Lim, I. (2007). Cueing training in the home improves gait-related mobility in Parkinson's disease: the RESCUE trial. *Journal of Neurology, Neurosurgery & Psychiatry, 78*(2), 134-140. https://doi.org/10.1136/jnnp.200X.097923

Nombela, C., Hughes, L. E., Owen, A. M., & Grahn, J. A. (2013). Into the groove: Can rhythm influence Parkinson's disease? *Neuroscience & Biobehavioral Reviews, 37*(10, Part 2), 2564-2570. https://doi.org/10.1016/j.neubiorev.2013.08.003

O'Konski, M., Bane, C., Hettinga, J., & Krull, K. (2010). Comparative effectiveness of exercise with Patterned Sensory Enhanced music and background music for long-term care residents. *Journal of Music Therapy, 47*(2), 120-136. https://doi.org/10.1093/jmt/47.2.120

Pasquini, J., Ceravolo, R., Qamhawi, Z., Lee, J.-Y., Deuschl, G., Brooks, D. J., Bonuccelli, U., & Pavese, N. (2018). Progression of tremor in early stages of Parkinson's disease: A clinical and neuroimaging study. *Brain, 141*(3), 811-821. https://doi.org/10.1093/brain/awx376

Pau, M., Corona, F., Pili, R., Casula, C., Sors, F., Agostini, T., Cossu, G., Guicciardi, M., & Murgia, M. (2016). Effects of physical rehabilitation integrated with rhythmic auditory stimulation on spatio-temporal and kinematic parameters of gait in Parkinson's disease. *Frontiers in Neurology, 7*(126). https://doi.org/10.3389/fneur.2016.00126

Pecenka, N., Engel, A., & Keller, P. (2013). Neural correlates of auditory temporal predictions during sensorimotor synchronization. *Frontiers in Human Neuroscience, 7*(380). https://doi.org/10.3389/fnhum.2013.00380

Peng, Y.-C., Lu, T.-W., Wang, T.-H., Chen, Y.-L., Liao, H.-F., Lin, K.-H., & Tang, P.-F. (2011). Immediate effects of therapeutic music on loaded sit-to-stand movement in children with spastic diplegia. *Gait & Posture, 33*(2), 274-278. https://doi.org/10.1016/j.gaitpost.2010.11.020

Raglio, A. (2015). Music therapy interventions in Parkinson's disease: The state-of-the-art. *Frontiers in Neurology, 6*, 185. https://doi.org/10.3389/fneur.2015.00185

Rohrer, B., Fasoli, S., Krebs, H. I., Hughes, R., Volpe, B., Frontera, W. R., Stein, J., & Hogan, N. (2002). Movement smoothness changes during stroke recovery. *Journal of Neuroscience, 22*(18), 8297-8304. https://doi.org/10.1523/jneurosci.22-18-08297.2002

Romero, D. H., & Stelmach, G. E. (2003). Changes in postural control with aging and Parkinson's disease. *IEEE Engineering in Medicine and Biology Magazine, 22*(2), 27-31. https://doi.org/10.1109/memb.2003.1195692

Romero, D. H., Van Gemmert, A. W. A., Adler, C. H., Bekkering, H., & Stelmach, G. E. (2003). Altered aiming movements in Parkinson's disease patients and elderly adults as a function of delays in movement onset. *Experimental Brain Research, 151*(2), 249-261. https://doi.org/10.1007/s00221-003-1452-2

Rose, D., Delevoye-Turrell, Y., Ott, L., Annett, L. E., & Lovatt, P. J. (2019). Music and metronomes differentially impact motor timing in people with and without Parkinson's disease: Effects of slow, medium, and fast tempi on entrainment and synchronization performances in finger tapping, toe tapping, and stepping on the spot tasks. *Parkinson's disease, 2019*, 6530838-6530838. https://doi.org/10.1155/2019/6530838

Sadagopan, N., & Smith, A. (2008). Developmental changes in the effects of utterance length and complexity on speech movement variability. *Journal of Speech, Language, and Hearing Research, 51*(5), 1138-1151. https://doi.org/10.1044/1092-4388(2008/06-0222)

Schwartze, M., & Kotz, S. A. (2016, 2016-January-18). Regional interplay for temporal processing in Parkinson's disease: possibilities and challenges. *Frontiers in Neurology, 6*(270). https://doi.org/10.3389/fneur.2015.00270

Smith, A., Goffman, L., Zelaznik, H. N., Ying, G., & McGillem, C. (1995). Spatiotemporal stability and patterning of speech movement sequences. *Experimental Brain Research, 104*(3), 493-501. https://doi.org/10.1007/BF00231983

Smith, A., Johnson, M., McGillem, C., & Goffman, L. (2000). On the assessment of stability and patterning of speech movements. *Journal of Speech, Language, and Hearing Research, 43*(1), 277-286. https://doi.org/10.1044/jslhr.4301.277

Stegemöller, E. L. (2014). Exploring a neuroplasticity model of music therapy. *Journal of Music Therapy, 51*(3), 211-227. https://doi.org/10.1093/jmt/thu023

Stegemöller, E. L. (2018). The brain and music. In A. J. Knight, A. B. LaGasse, & A. A. Clair (Eds.), *Music therapy: An introduction to the profession* (pp. 89-102). American Music Therapy Association.

Stegemöller, E. L., Izbicki, P., & Hibbing, P. (2018). The influence of moving with music on motor cortical activity. *Neuroscience Letters, 683*, 27-32. https://doi.org/10.1016/j.neulet.2018.06.030

Street, A. (2012). Combining functional and psychoanalytic techniques, ysing Rhythmic Auditory Stimulation (RAS) and songwriting to treat a man with a traumatic brain injury. *Voices: A World Forum for Music Therapy, 12*(3). https://doi.org/10.15845/voices.v12i3.673

Teulings, H. L., Contreras-Vidal, J. L., Stelmach, G. E., & Adler, C. H. (1997). Parkinsonism reduces coordination of fingers, wrist, and arm in fine motor control. *Experimental Neurology, 146*(1), 159-170. https://doi.org/10.1006/exnr.1997.6507

Thaut, C. P. (2014). Patterned Sensory Enhancement (PSE). In M. H. Thaut & V. Hoemberg (Eds.), *Handbook of neurologic music therapy* (pp. 106-115). Oxford University Press.

Thaut, C. P., & Rice, R. (2014). Rhythmic Auditory Stimulation (RAS). In M. H. Thaut & V. Hoemberg (Eds.), *Handbook of neurologic music therapy* (pp. 94-104). Oxford University Press.

Thaut, M. H. (2013). Entrainment and the motor system. *Music Therapy Perspectives, 31*(1), 31-34. https://doi.org/10.1093/mtp/31.1.31

Thaut, M. H. (2014). Assesment and the Transformational Design Model (TDM). In M. H. Thaut & V. Hoemberg (Eds.), *Handbook of neurologic muisc thearpy* (pp. 60-68). Oxford University Press.

Thaut, M. H., Kenyon, G. P., Hurt, C. P., McIntosh, G. C., & Hoemberg, V. (2002). Kinematic optimization of spatiotemporal patterns in paretic arm training with stroke patients. *Neuropsychologia, 40*(7), 1073-1081. https://doi.org/10.1016/S0028-3932(01)00141-5

Thaut, M. H., McIntosh, G. C., & Hoemberg, V. (2014). Neurologic Music Therapy: From social science to neuroscience. In M. H. Thaut & V. Hoemberg (Eds.), *Handbook of neurologic music therapy* (pp. 1-6). Oxford Univeristy Press.

Thaut, M. H., McIntosh, G. C., & Hoemberg, V. (2015). Neurobiological foundations of neurologic music therapy: Rhythmic entrainment and the motor system. *Frontiers in Psychology, 5*(1185). https://doi.org/10.3389/fpsyg.2014.01185

Thaut, M. H., McIntosh, G. C., Rice, R. R., Miller, R. A., Rathbun, J., & Brault, J. M. (1996). Rhythmic auditory stimulation in gait training for Parkinson's disease patients. *Movement Disorders, 11*(2), 193-200. https://doi.org/10.1002/mds.870110213

Viviani, P., Burkhard, P. R., Chiuvé, S. C., dell'Acqua, C. C., & Vindras, P. (2009). Velocity control in Parkinson's disease: A quantitative analysis of isochrony in scribbling movements. *Experimental Brain Research, 194*(2), 259-283. https://doi.org/10.1007/s00221-008-1695-z

Yamada, H. (2009). *The effect of patterned sensory enhancement on exercise adherence in older adults* (Publication Number 1473413) [M.M.E., University of Kansas]. ProQuest Dissertations & Theses Global. Ann Arbor. https://search.proquest.com/dissertations-theses/effect-patterned-sensory-enhancement-on-exercise/docview/304906734/se-2?accountid=10223