RHYTHMIC PROCESSES IN STUTTERING AND PARKINSON'S DISEASE

Simone Dalla Bella [1,2,3,4] and Simone Falk [1,3,5]

[1] International Laboratory for Brain, Music, and Sound Research (BRAMS), Montreal, QC, Canada

[2] Department of Psychology, University of Montreal, Montreal, QC, Canada

[3] Centre for Research on Brain, Language and Music (CRBLM), Montreal, QC, Canada

[4] University of Economics and Human Sciences in Warsaw, Warsaw, Poland

[5] Department of Linguistics and Translation, University of Montreal, Montreal, QC, Canada

1. INTRODUCTION

Stuttering and Parkinson's disease (PD) are complex neurological conditions characterized by disrupted motor control, which prominently manifests in speech and walking impairments. Within these disorders, an intriguing parallel emerges as both exhibit untimely initiation or termination of motor commands, leading to distinctive motor impairments. Stuttering, with its blockades, sound and syllable repetitions, and prolongations, significantly disrupts the smooth and rhythmic flow of speech (Bloodstein et al., 2021). In contrast, PD presents with dysfunctional gait and balance, along with freezing episodes, posing challenges to maintaining a regular rhythm while walking (Grabli et al., 2012; Kalia & Lang, 2015). These rhythmic alterations not only affect the motor functions but also extend to rhythm perception. Remarkably, they transcend the boundaries of specific motor effectors and encompass broader rhythmic domains. Therefore, it becomes crucial to explore the underlying mechanisms that contribute to these rhythmic disturbances across diverse motor behaviors and perceptual processes. In this chapter we try to unravel the hypothesis that motor deficits in stuttering and PD partly originate from alterations within the timing system responsible for temporal prediction (e.g., Schwartze & Kotz, 2013). Investigating the interplay between motor control and temporal processing in the two classes of disorders will help shedding light on shared mechanisms. Particular attention will be paid to rhythm-based interventions building on these shared mechanisms and potentially leading to innovative treatment strategies. In doing so, we adopt a multidisciplinary approach, integrating neurology, speech pathology, motor control, and cognitive neuroscience.

2. The Role of Rhythm in Developmental Stuttering

Neurodevelopmental stuttering is a childhood-onset speech motor disorder that significantly disrupts the flow of speech (ICD-11, 2023). It is reported since antiquity across languages and regions around the globe. It is more prevalent in young children (around 5-10% of children aged 2-3 years) compared to adolescents or adults (~1%, Yairi & Ambrose, 2013). In approximately 80% of affected children, symptoms naturally disappear within a few months to two years after stuttering onset, often before puberty (Yairi & Ambrose, 2004). However, some individuals continue to stutter into adulthood. Risk factors for persistent stuttering include co-occurring neurodevelopmental speech or language disorders (e.g., dyslexia, developmental language disorder), a family history of stuttering (with heredity estimates of 40-80%), late onset of stuttering (>4 years), and being male (Frigerio-Domingues & Drayna, 2017; Singer et al., 2020).

Stuttering hinders the flow of speech with involuntary sound and syllable repetitions and silent pauses (Guitar, 2012). While typical speech dysfluencies include pauses and repetitions, such as searching for words or correcting mispronunciations (Lickley, 2015), stuttering stands out by disrupting the start or continuation of speech, leading to irregular breaks in speech flow (Guitar, 2012). Stuttering is often associated with physical symptoms like muscle tension, facial grimacing, and involuntary movements (Bloodstein et al., 2021).

The arrhythmic character of stuttering is shaped by the randomness of symptoms. One individual's frequency and severity of symptoms can randomly change from mild to severe stuttering from one day or situation to the other (Tichenor & Yaruss, 2021). The temporal unpredictability of symptoms within a speech segment is probably one of the main reasons why stuttering is seen as a disorder disrupting the natural rhythm of speech. Stuttering's unpredictable nature tend to disrupt conversation flow, prompting interlocutors unfamiliar with this disorder to use correction strategies like completing sentences, interrupting or prematurely taking turns (Guitar, 2012). Conversely, people who stutter might employ avoidance tactics in conversations, such as changing or skipping words and using fillers to conceal stuttering or avoid taking turns (Tichenor & Yaruss, 2019). These attempts from both sides to restore a smoother flow of conversation or conceal the stuttering are ultimately ineffective. The continuous struggle with self-expression can cause frustration, leading to speech avoidance, together with feelings of guilt, shame, and fear, significantly affects their psychosocial well-being and may result in isolation or depression, underscoring stuttering's classification as a communication disorder (Bloodstein et al., 2021; DSM-5, 2013).

At the core, stuttering is believed to stem from malfunctioning speech motor planning. Various hypotheses share the idea that the timely initiation and termination of speech movements might be compromised because of faulty integration of information from the auditory and motor systems (Alm, 2004; Chang & Guenther, 2020; Civier et al., 2013; Harrington, 1988; Max et al., 2004; Smith & Weber, 2017). The motor system's predicted output may temporally not align with the actual auditory feedback, resulting in temporal conflicts and, ultimately, stuttering symptoms (Max et al., 2004). Consequently, the motor system struggles to provide accurate timing cues for fluent speech production (Alm, 2004). At the neuronal level, altered connectivity and structural changes in the auditory, motor control, and timing circuits, including the basal-ganglia-thalamo-cortical circuit, have been observed in individuals who stutter (Chang et al., 2008, 2015; Connally et al., 2018; Kronfeld-Duenias et al., 2016; Sommer et al., 2002). These changes affect speech production, auditory-motor learning, and information flow between left-hemispheric areas and subcortical structures (Chang &

Zhu, 2013; Giraud et al., 2008; Kell et al., 2018, see also Chang & Guenther, 2020). Structural alterations have also been reported in key structures within the left-dominant part of the networks (e.g., supplementary motor area, inferior frontal gyrus and premotor cortex, putamen and nucleus caudate; e.g., Beal et al., 2013, 2015; Chang & Guenther, 2020; Neef et al., 2015).

If the general timing network plays a role in stuttering, why would only speech be affected? Indeed, studies have shown that individuals who stutter exhibit distinct patterns in tasks involving metronome tapping, displaying less consistency and accuracy compared to their fluent peers, particularly those with moderate to high stuttering severity (Falk et al., 2015; Sares et al., 2019). Children who stutter also demonstrated weaker discrimination of musical rhythmic sequences, suggesting difficulties in generating an internal beat in both music and speech, at least in an English-speaking population (Wieland et al., 2015). These findings, in conjunction with neural observations, point towards the involvement of the broader timing network in stuttering.

3. Rhythm Disorders in Parkinson's Disease

After Alzheimer's disease, characterized by the gradual loss of cognitive function, memory impairment, and changes in behavior and personality, PD is the second most common neurodegenerative disorder, and the most common serious movement disorder (Hirtz et al., 2007). There are about 4 million patients worldwide suffering from PD (Andlin-Sobocki et al., 2005). The disorder is caused by the progressive loss of neurons in the substantia nigra, which disrupts dopaminergic projections to the basal ganglia (specifically, the caudate nucleus and putamen) and leads to the deregulation of basal ganglia-thalamo-cortical circuitry.

Three cardinal symptoms characterize PD, namely resting tremor, limb rigidity (stiffness and resistance to movement in the muscles, causing a reduced range of motion), and general slowness of movement and difficulty initiating and executing voluntary actions (bradykinesia / akinesia) (Jankovic, 2008; Kalia & Lang, 2015; Samii et al., 2004).

In addition to these cardinal symptoms, PD also presents with significant motor signs related to gait and balance. As PD progresses, the severity of these symptoms tends to increase (Bloem, 1992; Grabli et al., 2012; Koller & Montgomery, 1997). During the early stages, gait dysfunctions can be observed when patients engage in dual-task conditions, such as walking while simultaneously performing another task (e.g., speaking). These dual-task situations place demands on limited attentional resources and executive functions (Al-Yahya et al., 2011; Kelly et al., 2012). Gait alterations in PD include smaller and less regular steps due to shorter strides, compensatory adjustments in cadence (steps/min) to account for reduced stride length, reduced gait velocity, as well as festination and freezing (difficulty in initiating or stopping gait when turning or approaching an object) (Giladi, 2001; Grabli et al., 2012; Morris et al., 1994, 2001). All these alterations of walking lead to dysfunctional gait rhythm in PD. These deficits are a major cause of disability, hindering patients' mobility and independence, and a growing economic burden for the healthcare system (Grabli et al., 2012).

Notably, rhythm disorders apparent in Parkinsonian gait extend across motor domains. Rhythm disorders in PD are also found in orofacial rhythmic coordination (e.g., oral diadochokinesis tasks), where patients have difficulties in keeping a steady – isochronous – oral rhythm (Skodda et al., 2010), and in tapping tasks when they have to tap their hand or finger at a regular rhythm or to an external rhythmic stimulus (Benoit et al., 2014; Bieńkiewicz & Craig, 2015; Jones & Jahanshahi, 2014). Rhythm disorders in PD manifest also in perceptual tasks, in the absence of motor output, such as extracting the beat from a musical sequence (Grahn & Brett, 2009; Tolleson et al., 2015). Only a few studies have investigated the relationship between rhythm variability across different motor domains in PD. Evidence suggests a correlation between rhythmic features of gait and speech in PD (Cantiniaux et al., 2010). Recent research from our laboratory demonstrates a tight relationship between the variability of motor actions across various effectors (e.g., finger tapping, gait, oromotor system) and impaired beat perception, suggesting that a central mechanism related to rhythm processing may contribute to rhythm motor disorders across domains (Dalla Bella, 2022; Puyjarinet et al., 2019). Notably, these effects across motor domains, including speech production, are observed in spite of the variability of the rhythm class of language (French, English) (see also Chapters 11, 33, 30, 32, and 40, this Volume); altogether these findings support the concept of a central disorder, referred to as "general dysrhythmia," underlying rhythmic deficits in PD (Cantiniaux et al., 2010; Puyjarinet et al., 2019; Tolleson et al., 2015).

This parsimonious explanation of general rhythm disorders in Parkinson's disease is in keeping with the neuronal basis of the disease, involving basal-ganglia-cortical circuitries (Factor & Weiner, 2008), which play a role in rhythm processing and temporal prediction (Grahn & Brett, 2007, 2009; Schwartze & Kotz, 2013). Indeed, the core neural circuitry impacted by Parkinson's disease, which includes the basal ganglia, premotor cortex, and pre-supplementary motor area, is also involved in rhythm perception and production (Chen et al., 2008; Coull et al., 2011; Dalla Bella et al., 2017; Grahn & Brett, 2007; Grahn & Rowe, 2009; Repp, 2005; Repp & Su, 2013).

TABLE 45.1. BRIEF SUMMARY OF DIFFERENCES AND SIMILARITIES BETWEEN DEVELOPMENTAL STUTTERING AND PARKINSON'S DISEASE

	Stuttering	*Parkinson*
Disorder type	Neurodevelopmental	Neurodegenerative
Primary affected motor rhythm	Speech (syllabic rhythm, initiation, execution)	Gait (initiation and maintenance)
Other affected motor rhythms	Tapping (paced/unpaced)	Tapping (paced/unpaced) Oromotor coordination (diadocokinesis) Speech (dysarthria, stuttering)
Rhythmic perception affected?	Maybe (one study)	Yes
	Similarities between stuttering and PD	
Neural bases	Alterations in the basal-ganglia-thalamo-cortical network	
Main underlying mechanisms	Impaired temporal predictions and less automatized / de-automatized motor patterns	
Benefits from	Enhancing temporal cues, auditory pacing, training of auditory-motor patterns	

4. OVERLAPS BETWEEN DEVELOPMENTAL STUTTERING AND PARKINSON'S DISEASE

Despite significant clinical and age-related distinctions between stuttering and PD, both disorders share a dysfunction in the basal ganglia-cortical network, a critical component involved in rhythm processing and temporal prediction (see Table 45.1). This suggests that overlaps should be observed across the two classes of disorders. This section explores shared phenomena and mechanisms between PD and stuttering and highlights that both conditions can be considered as rhythmic-motor disorders, emphasizing their rhythmic aspects in addition to motor dysfunction.

4.1. Stuttering in Parkinson's Disease

Although dysarthria is the most prominent speech motor disorder in relation with PD (e.g., Duffy, 2015), stuttered dysfluencies are also found, in particular in more severe and longer-term cases of PD (Benke et al., 2000; Gooch et al., 2023). In the few studies available (see Gooch et al, 2023, for a summary), estimates of new-onset stuttering in PD patients range between 4 and 53%. Individuals who had once remitted from childhood stuttering were also found to present stuttering again at the onset of PD (Shahed & Jankovic, 2001).

4.2. "Freezing of Gait" versus "Gluency" in Speech

Alm (2021) recently discussed similarities between gait freezing in PD and stuttering in the "inability to move forward in a movement sequence", whether gait or speech. Freezing of gait implies a blockade appearing as a failure in gait initiation, or occurring abruptly while patients are walking; in the latter case, a sudden decrease of step length and increase of step frequency and step-to-step variability is observed prior to a complete blockade, which may lead to falling (e.g., Grabli et al., 2012). For stuttering, the term "gluency" has been coined for the subjective experience of being stuck and unable to control the articulators as wished (Van Riper, 1992).

4.3. Effects of Auditory Pacing

In developmental stuttering, we find "fluency-enhancing conditions" that can significantly reduce stuttering, sometimes to no stuttering symptoms at all. There are different forms of these conditions. Some of them temporarily change the way auditory feedback of speech is delivered (e.g., whispering, delaying auditory feedback, auditory masking with noise or music). Others provide auditory rhythmic cues or rhythmic enhancement (i.e., speaking with a metronome, singing, choral speech; Andrews et al., 1982; Ingham et al., 2009). However, the beneficial effect of fluency-inducing conditions wanes after stopping the cue or altered feedback. Interestingly, stuttering in PD has a long tradition of being described as neurogenic stuttering that should not respond to such fluency-enhancements (Krishnan & Tiwari, 2013). However, individuals with PD who stutter were found to respond to choral speech similar to individuals with developmental stuttering (Juste et al., 2018). Moreover, articulatory tools used in the therapy of neurodevelopmental stuttering, such as slowing speech rate as well as other articulatory techniques can also help individuals with PD who stutter with their speech. These results require more studies about the common grounds for speech and other dysfluencies in PD and developmental stuttering.

The effect of auditory pacing in PD is even more evident. Known as rhythmic auditory cueing (RAC), presenting a regular auditory stimulus such as a metronome or music with a salient beat improves significantly gait in PD patients (Ghai, Ghai, Schmitz, et al., 2018; Kwakkel et al., 2007; Fleming, 1942). The intervention involves instructing patients to walk in synchrony with a regular sound or music with a distinct beat, often tailored to their preferred cadence (Benoit et al., 2014; Elston et al., 2010; Enzensberger et al., 1997; Howe et al., 2003; McIntosh et al., 1997; Thaut et al., 1996). In the presence of a rhythmic stimulus PD patients typically walk faster, increase their step length (McIntosh et al., 1997), and reduce the frequency of freezing episodes (Arias & Cudeiro, 2010). As in stuttering, this immediate effect tends to disappear after the end of the stimulation.

4.4. Shared Mechanisms

Both stuttering and PD share a common rhythmic component associated with difficulties in generating precise internal timing for motor actions, such as gait coordination and speech articulation. This rhythmic deficit involves inaccurate temporal predictions governing motor commands, resulting in disrupted movement initiation or execution. Interestingly, in both cases, the presence of an external rhythmic stimulus can alleviate these difficulties by compensating for the internal prediction inaccuracies. These observations support the characterization of stuttering and PD as motor-rhythm disorders. Both conditions involve alterations in the neuronal circuitry (subcortical-cortical network) underlying rhythm perception, production, and temporal prediction. Tasks involving beat perception and synchronization recruit similar neuronal circuitries, including the basal ganglia, premotor cortex, and pre-supplementary motor area (Chen et al., 2008; Coull et al., 2011; Dalla Bella et al., 2017; Grahn & Brett, 2007; Grahn & Rowe, 2009; Repp, 2005; Repp & Su, 2013; Schwartze & Kotz, 2013).

Another important aspect of rhythm deficits in both stuttering and PD is the role of automatization. In PD, neurodegeneration leads to deautomatization of movement, resulting, among other symptoms, in poorer dual-task performance. This aspect seems to be less evident in stuttering. However, Alm (2021) recently proposed that stuttering may involve less automatized speech sequences within the basal ganglia motor loop during childhood (see also, Chang & Guenther, 2020). Stuttering symptoms would emerge during attempts to produce these poorly automatized sequences. De-automatization of speech production through the allocation of increased attentional resources, such as imitating others, speaking with an accent, or consciously altering speech rate and articulatory patterns, would then reduce stuttering. The effects of rhythmic fluency-enhancing conditions can be interpreted in a similar way, as strong beat-based rhythms provided by a metronome provide a temporal scaffolding supporting temporal predictions (Large & Jones, 1999; Schwartze & Kotz, 2013), capable of freeing up attentional resources.

5. Rhythm as a Viable Intervention for both Parkinson's Disease and Stuttering

The aforementioned overlaps between PD and stuttering point to common deficits in temporal prediction and automatization. This suggests that a) training temporal predictions for movement generation and b) automatizing newly acquired timing patterns might have therapeutic potential for both classes of disorders. It is worth noting, however, that while both conditions are associated with rhythm and timing deficits, and their neural underpinning of these disorders partially overlap, there are significant differences. PD primarily involves degeneration in the dopaminergic pathways within the basal ganglia, impacting motor control and automatization. In contrast, stuttering is associated with deregulation of basal ganglia-cortical circuitries but is not accompanied by neurodegeneration, suggesting a more functional or developmental anomaly. Moreover, the role of the dopaminergic system in stuttering is not clear, yet (Alm, 2021). Therefore, while temporal prediction and rhythm training might benefit both classes of disorders by engaging common neural circuits including the basal ganglia and motor cortical areas, distinct functional mechanisms may be exploited in the two cases. For PD, rhythm-based therapies might aim to counteract or bypass dopaminergic deficits, whereas in stuttering, the focus could be on strengthening the functional connectivity and efficiency of the motor circuits involved. This distinction underscores the importance of tailored therapeutic interventions that, while exploiting the shared role of rhythm and timing, are also sensitive to the unique neural substrates of each disorder.

5.1. Training Exploiting Rhythmic Stimulation in Parkinson's Disease

Several treatments are available to manage motor symptoms in PD. These include medication (like levodopa and dopamine agonists) (Connolly & Lang, 2014), surgical procedures (such as pallidotomy or thalamotomy) (Lozano et al., 2018), deep-brain stimulation (DBS) (Benabid et al., 1987; Kalia et al., 2013), and non-invasive options like physical therapy and neuromodulation techniques (transcranial magnetic stimulation or transcranial direct current stimulation) (Benninger & Hallett, 2015). Each treatment aims to compensate for dopamine loss or reduce the dysfunction in brain circuitries related to movement. In addition to pharmacotherapy and various other interventions, non-pharmacological treatments such as rhythmic auditory cueing (RAC) are recognized for their beneficial effects in managing PD symptoms. These rhythm-based therapies complement traditional treatments and are increasingly acknowledged for their role in improving motor symptoms in PD patients. More generally, rhythmic stimuli have shown beneficial effects on motor behavior in patients with movement disorders and older adults (Ghai, Ghai, & Effenberg, 2018; Ghai, Ghai, Schmitz, et al., 2018; Spaulding et al., 2013). Most studies have focused on gait disorders due to their functional relevance, impact on quality of life, and economic burden. In the management of PD, where the effectiveness of dopamine replacement therapy diminishes over time (Grabli et al., 2012; Sethi, 2008), there is a pressing need for innovative non-pharmacological approaches to improve gait. Rhythm-based interventions, such as walking to an auditory beat or participating in dance activities, hold promise in enhancing gait, quality of life, and social engagement among individuals with PD (for a review, see Dalla Bella, 2020). These interventions leverage rhythmic auditory cues to provide a temporal framework that facilitates movement initiation and coordination (Ghai, Ghai, Schmitz, et al., 2018; Spaulding et al., 2013).

RAC has as immediate beneficial effect on gait in PD (Arias & Cudeiro, 2010; Cochen De Cock et al., 2018; McIntosh et al., 1997). While these benefits tend to dissipate once the stimulation ceases, longer-term effects can be observed through RAC rehabilitation programs, as shown by Lim and collaborators (2005). These programs involve regular RAC-assisted walking sessions, resulting in increased walking speed and reduced freezing phenomena at the end of the rehabilitation, even in the absence of stimulation (Dalla Bella et al., 2017; Nieuwboer, 2008; Rochester et al., 2009). Similar motor benefits are observed with home-based RAC rehabilitation using a stimulating device (Nieuwboer et al., 2007). However, the long-term persistence of these effects and their interaction with neurodegenerative decline remain uncertain, with inconclusive evidence to date (Benoit et al., 2014; Marchese et al., 2000; Nieuwboer et al., 2001).

The exact nature of brain mechanisms underlying these beneficial effects still needs clarification. For example, the bases of RAC in PD is still a subject of ongoing debate (Dalla Bella et al., 2015; Dalla Bella et al., 2018; Nombela et al., 2013; for a review, see Dalla Bella, 2020). It is still unclear whether beneficial effects are mediated by spared brain mechanisms (cerebello-thalamo-cortical network) acting compensatorily, or by capitalizing on residual capacities of the impaired network in PD (basal-ganglia-thalamo-cortical network). However, emerging evidence suggests that these mechanisms may extend beyond gait-specific processes and instead involve a more general-purpose network that supports rhythm perception, production, and temporal prediction (Dalla Bella, 2020; Large & Jones, 1999; Piras & Coull, 2011; Schwartze & Kotz, 2013). This idea is supported by studies indicating improved rhythm perception following RAC training (Benoit et al., 2014) and the observation that gait improvement through RAC is associated with individual rhythm perception and production abilities (Cochen De Cock et al., 2018; Dalla Bella et al., 2017, 2018). Notably, this hypothesis aligns well with the aforementioned general dysrhythmia hypothesis (Cantiniaux et al., 2010; Puyjarinet et al., 2019; Tolleson et al., 2015) and provides a coherent framework for understanding the broader implications of rhythm interventions.

A hypothesis arising from this theory posits that rhythmic training targeting a specific effector (e.g., hand, finger) may yield positive effects on motor control and rhythmic behavior in other effectors (e.g., oromotor, gait). This transfer effect could be facilitated by the shared mechanisms supporting temporal prediction (Dalla Bella, 2022). To examine this hypothesis, we conducted a recent pilot study (Puyjarinet et al., 2022) involving patients with PD. During the study, participants underwent training using either a rhythmic tapping game (Rhythm Workers; Bégel et al., 2018; Dauvergne et al., 2018) or a non-rhythmic game (Tetris) over the course of one month. Both games were implemented as tablet apps. The rhythmic game required participants to tap along with various rhythmic auditory stimuli, with synchronization accuracy determining progress in the game. Remarkably, the rhythm intervention not only reduced motor variability in the trained motor domain (tapping), but also demonstrated a positive effect on an oromotor task (diadocokinesis task), unlike the control condition which showed no such effect. Moreover, these beneficial outcomes were correlated with improvements in rhythm perception. These promising findings provide evidence of transfer effects driven by rhythmic training in PD, and first causal evidence in support of the hypothesis of a general dysrhythmia in PD. If confirmed in further studies also involving other clinical populations these findings might have particular significance from a clinical standpoint, whereby the effects of rhythmic training may extend from one effector and motor actions to others. This highlights the potential of rhythmic interventions as a valuable clinical tool for addressing motor impairments in various conditions, including developmental stuttering.

5.2. Potential of Rhythmic Training in Developmental Stuttering

Two decades ago, it was proposed that explicitly training the basal ganglia timing network may benefit rhythmic speech production in stuttering (Alm, 2004; Fujii & Wan, 2014). However, to date, no therapeutic approach based on rhythmic pacing techniques has been established, as the effects tend to diminish immediately after the end of rhythmic stimulation. Some devices have been developed to mimic fluency-enhancing conditions, such as choral speech, during naturalistic speech interaction, with mixed results (e.g., Pollard et al., 2009). More recently, efforts have been focused on utilizing neuromodulation techniques to establish more efficient patterns of information flow in the brains of adults who stutter. For example, transcranial direct current stimulation (tDCS), a technique during which brain regions are stimulated with very low electrical current during the execution of a task, was used in combination with rhythmic pacing, such as speaking with a metronome or choral speech to enhance fluent speech production (Busan et al., 2021). Although first results are promising, further research is needed to determine the potential and the exact conditions under which these techniques should be applied.

Further exploration could focus on investigating whether intense or long-term rhythmic training could serve as a naturalistic approach for individuals who stutter to enhance their temporal predictions. An initial step would involve assessing the relationship between musical training and the occurrence, severity, or therapy outcomes of stuttering. If individuals who stutter exhibit significantly lower levels of musical training compared to the general population, or if lower severity or therapy success is associated with musical or rhythmic abilities, this would provide a basis for examining the effects of musical and rhythmic training on stuttering. Currently, only a limited number of studies have investigated the relationship between music and stuttering, primarily regarding immediate fluency-inducing effects, with (Falk, forthcoming) and Falk et al. (2018) providing comprehensive overviews. Secondly, it would be crucial to identify individual differences that distinguish which speakers who stutter would benefit from musical training versus those who would not. Lastly, research should assess whether general musical, non-verbal, or specifically verbal rhythmic training can produce transfer effects on self-paced everyday speech.

6. SUMMARY

Stuttering and PD exhibit different aetiologies, as well as notable clinical and age-related differences, which lead to classify them as separate disorders. In spite of these differences, though, both disorders share a dysfunction in the basal ganglia-cortical circuitries which plays a vital role in rhythm processing and temporal prediction. A pivotal notion in explaining this overlap is the concept of predictive timing, namely the ability to predict accurately the time of occurrence of an upcoming event (e.g., the next syllable, or the next step), based on the regular temporal structure of a sequence (Large & Jones, 1999; Piras & Coull, 2011; Schwartze & Kotz, 2013). Our review examines the behavioral – clinical manifestations - and neuronal overlaps of stuttering and PD, underscoring that both conditions involve alterations in the neuronal circuitry (subcortical-cortical network) underlying rhythm perception, production, and temporal prediction. For these reasons, we conclude that stuttering and PD can be classified as rhythmic-motor disorders, emphasizing the significance of rhythm in addition to motor dysfunction. This hypothesis has implications for novel intervention strategies exploiting shared neuronal circuitries underpinning temporal and rhythm processing, that could potentially benefit both stuttering and PD. While rhythm-based interventions like RAC have been widely examined in PD, their efficacy in stuttering warrants further investigation. The emergence of new technologies, such as mobile devices and serious games, offers opportunities to implement rhythmic training protocols in a variety of populations, including developmental stuttering (Agres et al., 2021; Dalla Bella, 2022). These advancements provide a platform to test the effectiveness of rhythmic training in improving temporal prediction in both PD and stuttering.

Acknowledgements

SDB is funded by a Discovery grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), and by a Canada Research Chair in music auditory-motor skill learning and new technologies. SF is funded by a Discovery grant from NSERC, and by a Canada Research Chair in interdisciplinary studies on rhythm and language acquisition.

Summary

In this review, we compare rhythmic dimensions of stuttering and Parkinson's disease, two neurological conditions leading to dysfluencies and disruptions in motor control in speech and walking, respectively. The findings indicate common grounds in rhythm-related symptoms and neuronal resources, underscoring the relevance of rhythm for the classification of both disorders.

Implications

The chapter helps to understand processes and neural resources underlying rhythmic alterations and temporal prediction in speech motor control and their links to gross motor function. The results will inform future research comparing speech and motor rhythms in different motor disorders including, but not limited to speech and language disorders.

Gains

Based on the view that stuttering and Parkinson's disease are rhythmic motor disorders, we can conceive new intervention strategies based on rhythm training. These rhythm-based interventions could motivate interdisciplinary research using new technologies and uniting scientists from the speech and language sciences as well as from cognitive (neuro)sciences.

7. REFERENCES

Agres, K. R., Schaefer, R. S., Volk, A., van Hooren, S., Holzapfel, A., Dalla Bella, S., Müller, M., de Witte, M., Herremans, D., Ramirez Melendez, R., Neerincx, M., Ruiz, S., Meredith, D., Dimitriadis, T., & Magee, W. L. (2021). Music, Computing, and Health: A Roadmap for the Current and Future Roles of Music Technology for Health Care and Well-Being. Music & Science, 4, 2059204321997709. https://doi.org/10.1177/2059204321997709

Alm, P. A. (2004). Stuttering and the basal ganglia circuits: A critical review of possible relations. Journal of Communication Disorders, 37(4), 325–369. https://doi.org/10.1016/j.jcomdis.2004.03.001

Alm, P. A. (2021). The Dopamine System and Automatization of Movement Sequences: A Review With Relevance for Speech and Stuttering. Frontiers in Human Neuroscience, 15, 661880. https://doi.org/10.3389/fnhum.2021.661880

Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., & Cockburn, J. (2011). Cognitive motor interference while walking: A systematic review and meta-analysis. Neuroscience and Biobehavioral Reviews, 35(3), 715–728. https://doi.org/10.1016/j.neubiorev.2010.08.008

Andlin-Sobocki, P., Jönsson, B., Wittchen, H.-U., & Olesen, J. (2005). Cost of disorders of the brain in Europe. European Journal of Neurology, 12 Suppl 1, 1–27. https://doi.org/10.1111/j.1468-1331.2005.01202.x

Andrews, G., Howie, P. M., Dozsa, M., & Guitar, B. E. (1982). Stuttering: Speech pattern characteristics under fluency-inducing conditions. Journal of Speech and Hearing Research, 25(2), 208–216.

Arias, P., & Cudeiro, J. (2010). Effect of rhythmic auditory stimulation on gait in Parkinsonian patients with and without freezing of gait. PloS One, 5(3), e9675. https://doi.org/10.1371/journal.pone.0009675

Beal, D. S., Gracco, V. L., Brettschneider, J., Kroll, R. M., & De Nil, L. F. (2013). A voxel-based morphometry (VBM) analysis of regional grey and white matter volume abnormalities within the speech production network of children who stutter. Cortex; a Journal Devoted to the Study of the Nervous System and Behavior, 49(8), 2151–2161. https://doi.org/10.1016/j.cortex.2012.08.013

Beal, D. S., Lerch, J. P., Cameron, B., Henderson, R., Gracco, V. L., & De Nil, L. F. (2015). The trajectory of gray matter development in Broca’s area is abnormal in people who stutter. Frontiers in Human Neuroscience, 9, 89. https://doi.org/10.3389/fnhum.2015.00089

Bégel, V., Seilles, A., & Dalla Bella, S. (2018). Rhythm Workers: A music-based serious game for training rhythm skills. Music & Science, 1, 2059204318794369. https://doi.org/10.1177/2059204318794369

Benabid, A. L., Pollak, P., Louveau, A., Henry, S., & de Rougemont, J. (1987). Combined (thalamotomy and stimulation) stereotactic surgery of the VIM thalamic nucleus for bilateral Parkinson disease. Applied Neurophysiology, 50(1–6), 344–346. https://doi.org/10.1159/000100803

Benke, T., Hohenstein, C., Poewe, W., & Butterworth, B. (2000). Repetitive speech phenomena in Parkinson's disease. Journal of Neurology, Neurosurgery, and Psychiatry, 69(3), 319–324. https://doi.org/10.1136/jnnp.69.3.319

Benninger, D. H., & Hallett, M. (2015). Non-invasive brain stimulation for Parkinson's disease: Current concepts and outlook 2015. NeuroRehabilitation, 37(1), 11–24. https://doi.org/10.3233/NRE-151237

Benoit, C.-E., Dalla Bella, S., Farrugia, N., Obrig, H., Mainka, S., & Kotz, S. A. (2014). Musically cued gait-training improves both perceptual and motor timing in Parkinson's disease. Frontiers in Human Neuroscience, 8, 494. https://doi.org/10.3389/fnhum.2014.00494

Bieńkiewicz, M. M. N., & Craig, C. M. (2015). Parkinson's Is Time on Your Side? Evidence for Difficulties with Sensorimotor Synchronization. Frontiers in Neurology, 6, 249. https://doi.org/10.3389/fneur.2015.00249

Bloem, B. R. (1992). Postural instability in Parkinson's disease. Clinical Neurology and Neurosurgery, 94 Suppl, S41-45. https://doi.org/10.1016/0303-8467(92)90018-x

Bloodstein, O., Ratner, N. B., & Brundage, S. B. (2021). A Handbook on Stuttering, Seventh Edition. Plural Publishing.

Busan, P., Moret, B., Masina, F., Del Ben, G., & Campana, G. (2021). Speech Fluency Improvement in Developmental Stuttering Using Non-invasive Brain Stimulation: Insights From Available Evidence. Frontiers in Human Neuroscience, 15, 662016. https://doi.org/10.3389/fnhum.2021.662016

Cantiniaux, S., Vaugoyeau, M., Robert, D., Horrelou-Pitek, C., Mancini, J., Witjas, T., & Azulay, J.-P. (2010). Comparative analysis of gait and speech in Parkinson's disease: Hypokinetic or dysrhythmic disorders? Journal of Neurology, Neurosurgery, and Psychiatry, 81(2), 177–184. https://doi.org/10.1136/jnnp.2009.174375

Chang, S.-E., Erickson, K. I., Ambrose, N. G., Hasegawa-Johnson, M. A., & Ludlow, C. L. (2008). Brain anatomy differences in childhood stuttering. NeuroImage, 39(3), 1333–1344. https://doi.org/10.1016/j.neuroimage.2007.09.067

Chang, S.-E., & Guenther, F. H. (2019). Involvement of the Cortico-Basal Ganglia-Thalamocortical Loop in Developmental Stuttering. Frontiers in Psychology, 10, 3088. https://doi.org/10.3389/fpsyg.2019.03088

Chang, S.-E., & Zhu, D. C. (2013). Neural network connectivity differences in children who stutter. Brain: A Journal of Neurology, 136(Pt 12), 3709–3726. https://doi.org/10.1093/brain/awt275

Chang, S.-E., Zhu, D. C., Choo, A. L., & Angstadt, M. (2015). White matter neuroanatomical differences in young children who stutter. Brain: A Journal of Neurology, 138(Pt 3), 694–711. https://doi.org/10.1093/brain/awu400

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Listening to musical rhythms recruits motor regions of the brain. Cereb Cortex, 18(12), 2844–2854. https://doi.org/10.1093/cercor/bhn042

Civier, O., Bullock, D., Max, L., & Guenther, F. H. (2013). Computational modeling of stuttering caused by impairments in a basal ganglia thalamo-cortical circuit involved in syllable selection and initiation. Brain and Language, 126(3), 263–278. https://doi.org/10.1016/j.bandl.2013.05.016

Cochen De Cock, V., Dotov, D. G., Ihalainen, P., Bégel, V., Galtier, F., Lebrun, C., Picot, M. C., Driss, V., Landragin, N., Geny, C., Bardy, B., & Dalla Bella, S. (2018). Rhythmic abilities and musical training in Parkinson's disease: Do they help? NPJ Parkinson's Disease, 4, 8. https://doi.org/10.1038/s41531-018-0043-7

Connally, E. L., Ward, D., Pliatsikas, C., Finnegan, S., Jenkinson, M., Boyles, R., & Watkins, K. E. (2018). Separation of trait and state in stuttering. Human Brain Mapping, 39(8), 3109–3126. https://doi.org/10.1002/hbm.24063

Connolly, B. S., & Lang, A. E. (2014). Pharmacological treatment of Parkinson disease: A review. JAMA, 311(16), 1670–1683. https://doi.org/10.1001/jama.2014.3654

Coull, J. T., Cheng, R. K., & Meck, W. H. (2011). Neuroanatomical and neurochemical substrates of timing. Neuropsychopharmacology, 36(1), 3–25. https://doi.org/10.1038/npp.2010.113

Dalla Bella, S. (2020). The use of rhythm in rehabilitation for patients with movement disorders. In L. L. Cuddy, S. Belleville, & A. Moussard (Eds.), Music and the Aging Brain (pp. 383–406). Academic Press. https://doi.org/10.1016/B978-0-12-817422-7.00015-8

Dalla Bella, S. (2022). Rhythmic serious games as an inclusive tool for music-based interventions. Annals of the New York Academy of Sciences, 1517(1), 15–24. https://doi.org/10.1111/nyas.14878

Dalla Bella, S., Benoit, C.-E., Farrugia, N., Keller, P. E., Obrig, H., Mainka, S., & Kotz, S. A. (2017). Gait improvement via rhythmic stimulation in Parkinson's disease is linked to rhythmic skills. Scientific Reports, 7, 42005. https://doi.org/10.1038/srep42005

Dalla Bella, S., Benoit, C.-E., Farrugia, N., Schwartze, M., & Kotz, S. A. (2015). Effects of musically cued gait training in Parkinson's disease: Beyond a motor benefit. Annals of the New York Academy of Sciences, 1337, 77–85. https://doi.org/10.1111/nyas.12651

Dalla Bella, S., Dotov, D., Bardy, B., & Cochen de Cock, V. (2018). Individualization of music-based rhythmic auditory cueing in Parkinson's disease. Annals of the New York Academy of Sciences, 1423, 308–317. https://doi.org/10.1111/nyas.13859

Dauvergne, C., Bégel, V., Gény, C., Puyjarinet, F., Laffont, I., & Dalla Bella, S. (2018). Home-based training of rhythmic skills with a serious game in Parkinson's disease: Usability and acceptability. Annals of Physical and Rehabilitation Medicine, 61(6), 380–385. https://doi.org/10.1016/j.rehab.2018.08.002

Diagnostic and statistical manual of mental disorders: DSM-5TM, 5th ed. (2013). American Psychiatric Publishing, Inc. https://doi.org/10.1176/appi.books.9780890425596

DO, S. A. F., & MD, W. J. W. (2007). Parkinson's Disease: Diagnosis and Clinical Management. Demos Medical Publishing.

Duffy, J. R. (2019). Motor Speech Disorders—4th Edition. Elsevier.

Elston, J., Honan, W., Powell, R., Gormley, J., & Stein, K. (2010). Do metronomes improve the quality of life in people with Parkinson's disease? A pragmatic, single-blind, randomized cross-over trial. Clinical Rehabilitation, 24(6), 523–532. https://doi.org/10.1177/0269215509360646

Enzensberger, W., Oberländer, U., & Stecker, K. (1997). [Metronome therapy in patients with Parkinson disease]. Der Nervenarzt, 68(12), 972–977. https://doi.org/10.1007/s001150050225

Falk, S. (forthcoming). Music and stuttering. In D. Sammler (Ed.), Oxford Handbook of Language and Music. Oxford University Press.

Falk, S., Müller, T., & Dalla Bella, S. (2015). Non-verbal sensorimotor timing deficits in children and adolescents who stutter. Frontiers in Psychology, 6, 847. https://doi.org/10.3389/fpsyg.2015.00847

Falk, S., Schreirer, R., & Russo, F. (2018). Singing and stuttering. In R. Heydon, D. Fancourt, & A. J. Cohen (Eds.), The Routledge companion to interdisciplinary studies in singing (pp. 50–60). Routledge.

Fleming, G. W. T. H. (1942). Methods of Treatment in Post-encephalitic Parkinsonism. By H. D. von Witzleben. New York: Grune & Stratton, 1942. Pp. 164. Journal of Mental Science, 88(373), 583–583. https://doi.org/10.1192/bjp.88.373.583-a

Frigerio-Domingues, C., & Drayna, D. (2017). Genetic contributions to stuttering: The current evidence. Molecular Genetics & Genomic Medicine, 5(2), 95–102. https://doi.org/10.1002/mgg3.276

Fujii, S., & Wan, C. Y. (2014). The Role of Rhythm in Speech and Language Rehabilitation: The SEP Hypothesis. Frontiers in Human Neuroscience, 8, 777. https://doi.org/10.3389/fnhum.2014.00777

Ghai, S., Ghai, I., & Effenberg, A. O. (2018). Effect of Rhythmic Auditory Cueing on Aging Gait: A Systematic Review and Meta-Analysis. Aging and Disease, 9(5), 901–923. https://doi.org/10.14336/AD.2017.1031

Ghai, S., Ghai, I., Schmitz, G., & Effenberg, A. O. (2018). Effect of rhythmic auditory cueing on parkinsonian gait: A systematic review and meta-analysis. Scientific Reports, 8(1), 506. https://doi.org/10.1038/s41598-017-16232-5

Giladi, N. (2001). Freezing of gait. Clinical overview. Advances in Neurology, 87, 191–197.

Giraud, A.-L., Neumann, K., Bachoud-Levi, A.-C., von Gudenberg, A. W., Euler, H. A., Lanfermann, H., & Preibisch, C. (2008). Severity of dysfluency correlates with basal ganglia activity in persistent developmental stuttering. Brain and Language, 104(2), 190–199. https://doi.org/10.1016/j.bandl.2007.04.005

Gooch, E. A., Horne, K.-L., Melzer, T. R., McAuliffe, M. J., MacAskill, M., Dalrymple-Alford, J. C., Anderson, T. J., & Theys, C. (2023). Acquired Stuttering in Parkinson's Disease. Movement Disorders Clinical Practice, 10(6), 956–966. https://doi.org/10.1002/mdc3.13758

Grabli, D., Karachi, C., Welter, M. L., Lau, B., Hirsch, E. C., Vidailhet, M., & Francois, C. (2012). Normal and pathological gait: What we learn from Parkinson's disease. Journal of Neurology, Neurosurgery and Psychiatry, 83(10), 979–985. https://doi.org/10.1136/jnnp-2012-302263

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., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. Cortex, 45(1), 54–61. https://doi.org/10.1016/j.cortex.2008.01.005

Grahn, J. A., & Rowe, J. B. (2009). Feeling the beat: Premotor and striatal interactions in musicians and nonmusicians during beat perception. Journal of Neuroscience, 29(23), 7540–7548. https://doi.org/10.1523/JNEUROSCI.2018-08.2009

Guitar, B. (2012). Stuttering: An Integrated Approach to Its Nature and Treatment. Lippincott Williams & Wilkins.

Harrington, J. (1988). Stuttering, delayed auditory feedback, and linguistic rhythm. Journal of Speech and Hearing Research, 31(1), 36–47. https://doi.org/10.1044/jshr.3101.36

Hirtz, D., Thurman, D. J., Gwinn-Hardy, K., Mohamed, M., Chaudhuri, A. R., & Zalutsky, R. (2007). How common are the "common" neurologic disorders? Neurology, 68(5), 326–337. https://doi.org/10.1212/01.wnl.0000252807.38124.a3

Howe, T. E., Lövgreen, B., Cody, F. W. J., Ashton, V. J., & Oldham, J. A. (2003). Auditory cues can modify the gait of persons with early-stage Parkinson's disease: A method for enhancing parkinsonian walking performance? Clinical Rehabilitation, 17(4), 363–367. https://doi.org/10.1191/0269215503cr621oa

ICD-11 for Mortality and Morbidity Statistics. (n.d.). Retrieved July 7, 2023, from https://icd.who.int/browse11/l-m/en

Ingham, R. J., Bothe, A. K., Jang, E., Yates, L., Cotton, J., & Seybold, I. (2009). Measurement of speech effort during fluency-inducing conditions in adults who do and do not stutter. Journal of Speech, Language, and Hearing Research, 52(5), 1286–1301. https://doi.org/10.1044/1092-4388(2009/08-0181)

Jankovic, J. (2008). Parkinson's disease: Clinical features and diagnosis. Journal of Neurology, Neurosurgery, and Psychiatry, 79(4), 368–376. https://doi.org/10.1136/jnnp.2007.131045

Jones, C. R. G., & Jahanshahi, M. (2014). Contributions of the Basal Ganglia to Temporal Processing: Evidence from Parkinson's Disease. Timing & Time Perception, 2(1), 87–127. https://doi.org/10.1163/22134468-00002009

Juste, F. S., Sassi, F. C., Costa, J. B., & de Andrade, C. R. F. (2018). Frequency of speech disruptions in Parkinson's Disease and developmental stuttering: A comparison among speech tasks. PloS One, 13(6), e0199054. https://doi.org/10.1371/journal.pone.0199054

Kalia, L. V., & Lang, A. E. (2015). Parkinson’s disease. Lancet, 386(9996), 896–912. https://doi.org/10.1016/s0140-6736(14)61393-3

Kalia, S. K., Sankar, T., & Lozano, A. M. (2013). Deep brain stimulation for Parkinson’s disease and other movement disorders. Current Opinion in Neurology, 26(4), 374–380. https://doi.org/10.1097/WCO.0b013e3283632d08

Kell, C. A., Neumann, K., Behrens, M., von Gudenberg, A. W., & Giraud, A.-L. (2018). Speaking-related changes in cortical functional connectivity associated with assisted and spontaneous recovery from developmental stuttering. Journal of Fluency Disorders, 55, 135–144. https://doi.org/10.1016/j.jfludis.2017.02.001

Kelly, V. E., Eusterbrock, A. J., & Shumway-Cook, A. (2012). A review of dual-task walking deficits in people with Parkinson’s disease: Motor and cognitive contributions, mechanisms, and clinical implications. Parkinson’s Disease, 2012, 918719. https://doi.org/10.1155/2012/918719

Koller, W. C., & Montgomery, E. B. (1997). Issues in the early diagnosis of Parkinson’s disease. Neurology, 49(1), S10-25. https://doi.org/10.1212/wnl.49.1_suppl_1.s10

Krishnan, G., & Tiwari, S. (2013). Differential diagnosis in developmental and acquired neurogenic stuttering: Do fluency-enhancing conditions dissociate the two? Journal of Neurolinguistics, 26(2), 252–257. https://doi.org/10.1016/j.jneuroling.2012.09.001

Kronfeld-Duenias, V., Amir, O., Ezrati-Vinacour, R., Civier, O., & Ben-Shachar, M. (2016). Dorsal and ventral language pathways in persistent developmental stuttering. Cortex, 81, 79–92. https://doi.org/10.1016/j.cortex.2016.04.001

Kwakkel, G., de Goede, C. J. T., & van Wegen, E. E. H. (2007). Impact of physical therapy for Parkinson’s disease: A critical review of the literature. Parkinsonism & Related Disorders, 13, S478–S487. https://doi.org/10.1016/s1353-8020(08)70053-1

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. Psychological Review, 106, 119–159. https://doi.org/10.1037/0033-295X.106.1.119

Lickley, R. J. (2015). Fluency and Disfluency. In The Handbook of Speech Production (pp. 445–474). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118584156.ch20

Lim, I., van Wegen, E., de Goede, C., Deutekom, M., Nieuwboer, A., Willems, A., Jones, D., Rochester, L., & Kwakkel, G. (2005). Effects of external rhythmical cueing on gait in patients with Parkinson’s disease: A systematic review. Clinical Rehabilitation, 19(7), 695–713. https://doi.org/10.1191/0269215505cr906oa

Lozano, C. S., Tam, J., & Lozano, A. M. (2018). The changing landscape of surgery for Parkinson’s Disease. Movement Disorders: Official Journal of the Movement Disorder Society, 33(1), 36–47. https://doi.org/10.1002/mds.27228

Marchese, R., Diverio, M., Zucchi, F., Lentino, C., & Abbruzzese, G. (2000). The role of sensory cues in the rehabilitation of parkinsonian patients: A comparison of two physical therapy protocols. Movement Disorders, 15(5), 879–883. https://doi.org/10.1002/1531-8257(200009)15:5<879::aid-mds1018>3.0.co;2-9

Max, L., Guenther, F. H., Gracco, V. L., Ghosh, S. S., & Wallace, M. E. (2004). Unstable or Insufficiently Activated Internal Models and Feedback-Biased Motor Control as Sources of Dysfluency: A Theoretical Model of Stuttering. Contemporary Issues in Communication Science and Disorders, 31, 105–122. https://doi.org/10.1044/cicsd_31_S_105

McIntosh, G. C., Brown, S. H., Rice, R. R., & Thaut, M. H. (1997). Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. Journal of Neurology, Neurosurgery, and Psychiatry, 62(1), 22–26. https://doi.org/10.1136/jnnp.62.1.22

Morris, M. E., Huxham, F., McGinley, J., Dodd, K., & Iansek, R. (2001). The biomechanics and motor control of gait in Parkinson disease. Clinical Biomechanics, 16(6), 459–470. https://doi.org/10.1016/s0268-0033(01)00035-3

Morris, M. E., Iansek, R., Matyas, T. A., & Summers, J. J. (1994). Ability to modulate walking cadence remains intact in Parkinson's disease. Journal of Neurology, Neurosurgery, and Psychiatry, 57(12), 1532–1534. https://doi.org/10.1136/jnnp.57.12.1532

Neef, N. E., Anwander, A., & Friederici, A. D. (2015). The Neurobiological Grounding of Persistent Stuttering: From Structure to Function. Current Neurology and Neuroscience Reports, 15(9), 63. https://doi.org/10.1007/s11910-015-0579-4

Nieuwboer, A. (2008). Cueing for freezing of gait in patients with Parkinson's disease: A rehabilitation perspective. Movement Disorders, 23 Suppl 2, S475-481. https://doi.org/10.1002/mds.21978

Nieuwboer, A., De Weerdt, W., Dom, R., Truyen, M., Janssens, L., & Kamsma, Y. (2001). The effect of a home physiotherapy program for persons with Parkinson's disease. Journal of Rehabilitation Medicine, 33(6), 266–272. https://doi.org/10.1080/165019701753236455

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, and 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 and Biobehavioral Reviews, 37(10), 2564–2570. https://doi.org/10.1016/j.neubiorev.2013.08.003

Piras, F., & Coull, J. T. (2011). Implicit, predictive timing draws upon the same scalar representation of time as explicit timing. PLoS One, 6(3), e18203. https://doi.org/10.1371/journal.pone.0018203

Pollard, R., Ellis, J. B., Finan, D., & Ramig, P. R. (2009). Effects of the SpeechEasy on objective and perceived aspects of stuttering: A 6-month, phase I clinical trial in naturalistic environments. Journal of Speech, Language, and Hearing Research, 52(2), 516–533. https://doi.org/10.1044/1092-4388(2008/07-0204)

Puyjarinet, F., Bégel, V., Geny, C., Driss, V., Cuartero, M.-C., De Cock, V. C., Pinto, S., & Dalla Bella, S. (2022). At-Home Training With a Rhythmic Video Game for Improving Orofacial, Manual, and Gait Abilities in Parkinson's Disease: A Pilot Study. Frontiers in Neuroscience, 16, 874032. https://doi.org/10.3389/fnins.2022.874032

Puyjarinet, F., Bégel, V., Gény, C., Driss, V., Cuartero, M.-C., Kotz, S. A., Pinto, S., & Dalla Bella, S. (2019). Heightened orofacial, manual, and gait variability in Parkinson's disease results from a general rhythmic impairment. NPJ Parkinson's Disease, 5, 19. https://doi.org/10.1038/s41531-019-0092-6

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. Psychonomic Bulletin & Review, 12(6), 969–992. https://doi.org/10.3758/bf03206433

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006-2012). Psychonomic Bulletin & Review, 20(3), 403–452. https://doi.org/10.3758/s13423-012-0371-2

Rochester, L., Burn, D. J., Woods, G., Godwin, J., & Nieuwboer, A. (2009). Does auditory rhythmical cueing improve gait in people with Parkinson's disease and cognitive impairment? A feasibility study. Movement Disorders, 24(6), 839–845. https://doi.org/10.1002/mds.22400

Samii, A., Nutt, J. G., & Ransom, B. R. (2004). Parkinson's disease. Lancet, 363(9423), 1783–1793. https://doi.org/10.1016/s0140-6736(04)16305-8

Sares, A. G., Deroche, M. L. D., Shiller, D. M., & Gracco, V. L. (2019). Adults who stutter and metronome synchronization: Evidence for a nonspeech timing deficit. Annals of the New York Academy of Sciences, 1449(1), 56–69. https://doi.org/10.1111/nyas.14117

Schwartze, M., & Kotz, S. A. (2013). A dual-pathway neural architecture for specific temporal prediction. Neuroscience and Biobehavioral Reviews, 37(10), 2587–2596. https://doi.org/10.1016/j.neubiorev.2013.08.005

Sethi, K. (2008). Levodopa unresponsive symptoms in Parkinson disease. Movement Disorders, 23, S521-533. https://doi.org/10.1002/mds.22049

Shahed, J., & Jankovic, J. (2001). Re-emergence of childhood stuttering in Parkinson's disease: A hypothesis. Movement Disorders, 16(1), 114–118. https://doi.org/10.1002/1531-8257(200101)16:1<114::aid-mds1004>3.0.co;2-2

Singer, C. M., Hessling, A., Kelly, E. M., Singer, L., & Jones, R. M. (2020). Clinical Characteristics Associated With Stuttering Persistence: A Meta-Analysis. Journal of Speech, Language, and Hearing Research, 63(9), 2995–3018. https://doi.org/10.1044/2020_JSLHR-20-00096

Skodda, S., Flasskamp, A., & Schlegel, U. (2010). Instability of syllable repetition as a model for impaired motor processing: Is Parkinson's disease a "rhythm disorder"? Journal of Neural Transmission, 117(5), 605–612. https://doi.org/10.1007/s00702-010-0390-y

Smith, A., & Weber, C. (2017). How Stuttering Develops: The Multifactorial Dynamic Pathways Theory. Journal of Speech, Language, and Hearing Research, 60(9), 2483–2505. https://doi.org/10.1044/2017_JSLHR-S-16-0343

Sommer, M., Koch, M. A., Paulus, W., Weiller, C., & Büchel, C. (2002). Disconnection of speech-relevant brain areas in persistent developmental stuttering. Lancet, 360(9330), 380–383. https://doi.org/10.1016/S0140-6736(02)09610-1

Spaulding, S. J., Barber, B., Colby, M., Cormack, B., Mick, T., & Jenkins, M. E. (2013). Cueing and gait improvement among people with Parkinson's disease: A meta-analysis. Archives of Physical Medicine and Rehabilitation, 94(3), 562–570. https://doi.org/10.1016/j.apmr.2012.10.026

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

Tichenor, S. E., & Yaruss, J. S. (2019). Group Experiences and Individual Differences in Stuttering. Journal of Speech, Language, and Hearing Research, 62(12), 4335–4350. https://doi.org/10.1044/2019_JSLHR-19-00138

Tichenor, S. E., & Yaruss, J. S. (2021). Variability of Stuttering: Behavior and Impact. American Journal of Speech-Language Pathology, 30(1), 75–88. https://doi.org/10.1044/2020_AJSLP-20-00112

Tolleson, C. M., Dobolyi, D. G., Roman, O. C., Kanoff, K., Barton, S., Wylie, S. A., Kubovy, M., & Claassen, D. O. (2015). Dysrhythmia of timed movements in Parkinson's disease and freezing of gait. Brain Research, 1624, 222–231. https://doi.org/10.1016/j.brainres.2015.07.041

Van Riper, C. (1992). Stuttering? Journal of Fluency Disorders, 17(1), 81–84. https://doi.org/10.1016/0094-730X(92)90025-L

Wieland, E. A., McAuley, J. D., Dilley, L. C., & Chang, S. E. (2015). Evidence for a rhythm perception deficit in children who stutter. Brain and Language, 144, 26–34. https://doi.org/10.1016/j.bandl.2015.03.008

Yairi, E., & Ambrose, N. (2013). Epidemiology of stuttering: 21st century advances. Journal of Fluency Disorders, 38(2), 66–87. https://doi.org/10.1016/j.jfludis.2012.11.002

Yairi, E., & Ambrose, N. G. (2004). Early Childhood Stuttering. PRO-ED, Inc.