No cover image available

The Oxford Handbook of Language and Music
(In Progress)
Daniela Sammler (ed.)
https://doi.org/10.1093/oxfordhb/9780192894700.001.0001
Published: 20 March 2025 - **Online ISBN:** 9780191915581 **Print ISBN:** 9780192894700

Search in this book

CHAPTER

Music and stuttering

Simone Falk

https://doi.org/10.1093/oxfordhb/9780192894700.013.0036
Published: 20 March 2025

Abstract

This chapter summarizes what is known about musical performance in stuttering. It shows how individuals who stutter differ in some musical abilities and how they experience music as professional musicians. It discusses why musical activities can affect motor networks in the brain and thereby, at least temporarily, reduce stuttering symptoms. It outlines different pathways for future research into musical abilities in individuals who stutter and how findings could contribute to our understanding of stuttering, specifically, and communication disorders more generally. In sum, the chapter demonstrates that stuttering elucidates the links between music and speech production, in particular in the domain of rhythm.

Keywords: stuttering, articulation, fluency, communication disorders, singing, rhythm, speech timing

Subject: Phonetics and Phonology, Psycholinguistics, Linguistics

Series: Oxford Handbooks

Collection: Oxford Handbooks Online

1 Introduction

Skilled movement is the basis of musical mastery as well as of speech. Speaking is like playing Rimsky-Korsakoff's 'flight of the bumblebee' at 15 notes per second. Whoever has seen an advanced musician play this piece knows how fast and accurate finger movements need to be to achieve this speed. From a speaking perspective, this pace is almost normal. An average pace of speech comprises 4 to 6 syllables per second, which means around 10 to 20 different sounds per second. This process engages fine and rapid coordination of up to 100 muscles per second (Lenneberg 1967). Hence, speaking is among the most complex and sophisticated human fine motor skills. It comes with no surprise that learning to speak takes time. Speech acquisition is a process that goes far beyond childhood. It takes up to 21 years until all articulatory and acoustic aspects of speech production in one's native language are refined according to their typical adult form (Smith 2010).

From a purely motor point of view, music and speech may be closer during development than we think. To gain insights into this potential relation, the present chapter examines the case of stuttering and what happens to speaking and musical skills when the typical pathway of speech motor acquisition is disturbed during development. This chapter will also explore some ideas on how musical training might benefit individuals who stutter—a topic that has received little attention in the literature so far. Stuttering—also called stammering or child-onset fluency disorder (DSM-V; American Psychiatric Association 2013)—is a neurodevelopmental speech fluency disorder (ICD-11; World Health Organization 2019/2021). As outlined in the first section of the chapter, it has a major impact on the act of speaking and on communication as it generates involuntary disruptions of the motor flow of speech. One prominent hypothesis posits that stuttering results from alterations in sensorimotor timing and associated neural circuits. This section will also present the neural circuits involved in stuttering and potential alterations compared to typical speech motor acquisition.

The second section is dedicated to the links between music and stuttering. It discusses whether sensorimotor timing deficits in stuttering may also affect non-verbal tasks. It presents some prominent cases of musicians who stutter as well as musical activities such as singing or speaking with a rhythm that can reduce stuttering symptoms to a minimum. The final part of the chapter discusses how musical training could impact different aspects of stuttering and how music could be integrated in intervention.

2 What is stuttering?

Dysfluencies are a regular part of everyday speech. Hesitations, word and phrase repetitions, interjections, and self-corrections are markers of ongoing speech and language planning. However, stuttered dysfluencies are different from these types of dysfluencies. Stuttering is characterized by sound, whole and part-syllable repetitions (like 'la-la-la-large'), or prolongations (like saying 'mmmmmmouse' with a stretched /m/). Blocks may occur suddenly in the middle of a phrase or a word (like 'p.......(pause)... pizza') during which the speaker tries to utter the word he or she is intending to say. Importantly, stuttered dysfluencies, unlike regular dysfluencies, are thought to originate from speech motor processes underlying articulation, and *not* from speech or language planning or word finding difficulties (Smith and Weber 2016; Walsh et al. 2015). However, stuttering is not only about fluent speech and its disturbance. Stuttering can disrupt communication in a major way, not only because it affects the flow of conversation but also because people who stutter may lose confidence in their speech and communicative capacities. Speaking can be experienced as effortful, a source of anxiety, and social failure. In severe cases, people who stutter may avoid certain communicative situations or partners, isolate from others, loose self-esteem, and develop negative feelings towards themselves (Bloodstein and Bernstein Ratner 2008; Guitar 2014). Moreover, stuttering is subject to a great deal of variability among different persons and situations (Tichenor and Yaruss 2021). Individuals who stutter report having phases during which they speak perfectly fluently while they experience many stuttering events on other occasions. Stressful situations, higher cognitive load, or being emotional might lead to more stuttering. The variability of stuttering is highly unpredictable, which is an additional burden in coping with stuttering in daily life.

2.1 Stuttering and its occurrence

Like many neurodevelopmental disorders, stuttering starts early in childhood, most often before the age of 6 years. Due to its atypical dysfluencies, stuttering can be detected by caregivers as early as first multi-word utterances appear, from 2 years of age onwards (Yairi and Ambrose 2004). This is an early age compared to other neurodevelopmental speech and language disorders such as speech sound disorder, dyslexia, or developmental language disorders that are typically diagnosed at later preschool age or even school age. Stuttering is reported in an estimated 5–10 per cent of children (Yairi and Ambrose 2013), although more children might experience a short and transient period of stuttering. Developmental stuttering is officially diagnosed, when stuttering persists longer than six months (Yairi and Ambrose 1999). It is noteworthy that developmental stuttering is often accompanied by other developmental conditions, although the nature of this relation and the underlying neural correlates remain largely unexplored. Recent large-scale studies in the United States indicate that an estimated 60 per cent of children who stutter display one or more other developmental conditions (e.g. developmental language disorder, dyslexia, attention-deficit hyperactivity disorder a.o.). This number would be 5.5 times higher than in children who do not stutter (Briley and Ellis 2018; Choo et al. 2020).

Around 80 per cent of children who stutter will stop stuttering before adolescence. A majority of them will naturally remit during the first 2 years following stuttering onset (i.e. most often before 6 years of age, Bloodstein and Bernstein Ratner 2008; Yairi and Ambrose 2004). Persistent stuttering continues to be present for a year or more, and even in adulthood. In adults, an estimated 1–3 per cent of the population self-report persistent stuttering (American Speech-Language-Hearing Association, n.d. ; STAMMA 2022). Persistent stuttering at adulthood shows a prominent gender bias, with 80 per cent of the adult population who stutters being male (Yairi and Ambrose 2013). Already at pre-school age, boys who stutter are 1.5 times more likely to stutter for a longer period of time than girls who stutter at the same age (Singer et al. 2020). Boys who stutter, at 4 years of age, also show a lag in the maturation of speech movements compared to children who do not stutter, but girls who stutter do not (Walsh et al. 2018). Beyond gender, there are several risk factors to develop persistent stuttering. Persistence is higher in children who start to stutter after 3.5 years of age, who have a family history of stuttering (Frigerio-Domingues and Drayna 2017; see also Gingras and Drayna, this volume), and who have concurrent speech and language problems (Singer et al. 2020). Some studies also point to a relevant link between lesser phonological and articulatory skills and stuttering persistence (e.g. Spencer and Weber-Fox 2014).

Stuttering intervention with persistent pre-school and early school children heavily relies on the implication of parents. One direct intervention scheme is the Lidcombe Program that uses an operant conditioning approach through which parents are trained to provide verbal feedback on speech quality (e.g. 'smooth' or 'bumpy') to positively reinforce fluent speech in children (Onslow et al. 2003). Indirect approaches consist in reducing the complexity of children's speech environment and daily life. Here, parents are asked to reduce sources of stress in children's daily schedules and time pressure, and review their communication behaviour during conversation (e.g. by slowing down their own speech rate, providing full attention to the child when talking to her, etc.; see e.g. Millard et al. 2018, for a therapy programme). Both techniques show effects in reducing stuttering symptoms, although it is still unknown whether they are effective in fostering/speeding recovery from stuttering above and beyond spontaneous remission rates (e.g. de Sonneville-Koedoot et al. 2015).

Stuttering intervention at later school age and adult age aims to provide articulatory techniques to manage and reduce the occurrence of stuttering events. An equally important aim is to ease the potential socio-emotional burden (i.e. desensitization, reducing avoidance of speaking, anxiety, and self-stigma, enhancing self-esteem and empowerment). Among the articulatory techniques, *fluency-shaping* is used to avoid stuttering symptoms and reduce tension by training individuals to speak in a highly controlled way (e.g. smooth onsets, prolonged vowels, controlled speech rate, pausing, and breathing; e.g. O'Brian et al. 2003; Webster 1977). *Stuttering modification* can be used to reduce the tension of an upcoming or ongoing stuttering event, and to foster fluent speech after a stuttering event (e.g. van Riper 1982; van Riper and Emerick 1984). Articulatory techniques take a long time to learn, and individuals are accompanied over a longer period of time by speech-language therapist to apply them in their daily life.

Overall, evidence is sparse that stuttering intervention can make stuttering disappear. However, interventions can reduce the occurrence and severity of stuttering symptoms as well as help speakers who stutter to improve their reaction and perception of themselves and their stuttering as well as to deal with reactions from their interlocutors (Guitar 2014; for recent information on intervention, consult the 'Stuttering' section of the website of the American Speech-Language-Hearing Association, n.d.).

2.2 Stuttering and altered timing mechanisms

In the framework of prominent neuro-computational speech production models (DiVA/GODiVA; see also Zuk et al., this volume), stuttering symptoms are described as the consequence of malfunctioning planning mechanisms that initiate or sustain the execution of speech movements in time (see also Chang and Guenther 2020, for an overview). Thereby, stuttering is different from e.g. childhood apraxia of speech that features symptoms attributed to faulty or instable motor programmes of sounds and syllables (e.g. articulatory searching behaviour, speech sound errors, and distortions; see Aichert and Ziegler, this volume). As a developmental fluency disorder, it is closer to cluttering, which, in contrast to stuttering, displays reduced speech intelligibility and a notable deregulation of speech rate (Van Zaalen-op't Hof et al. 2009). Untimely initiation and termination of speech motor commands are supposed to be at the core of stuttering (Chang and Guenther 2020; Civier et al. 2013). For example, a block might occur when a syllable's motor programme is not initiated in time. Involuntary repetitions of segments or syllables are provoked when an ongoing speech motor programme is not terminated on time and hinders the activation of the next motor programme, resulting in a reset of the ongoing motor programme (Civier et al. 2013).

Current research links untimely speech motor control in stuttering to atypical sensorimotor processes. In particular, processes related to monitoring one's own voice while speaking (auditory feedback) may not be aligned with the timing of actual speech production in stuttering (e.g. Max et al. 2004). Speakers who stutter show a less flexible (i.e. slower and weaker) response to experimental online manipulation of auditory feedback (e.g. shifting pitch or stretching durations of sounds) during articulation than speakers who do not stutter (e.g. Cai et al. 2014; Cai et al. 2012). In 2010, Civier and colleagues made a computer stutter by programming it in such a way that it was too much relying on auditory feedback to control speech movements. Auditory feedback processing is relatively slow (a delay of 20–30 ms is possible due to the sensory pathways involved) compared to the rapidity of ongoing motor execution. Civier and colleagues observed timing errors and resets of ongoing motor programmes with increasing delays during auditory-motor integration (Civier et al. 2010; but see also Terband et al. 2009, for a similar modelling for apraxia of speech).

In addition, neural activation of the auditory system seems already reduced *before* speech onset in adults who stutter compared to adults who do not stutter (Daliri and Max 2015a, 2015b, 2018). Daliri and Max (2018) proposed that adults who stutter might not be able to pre-set the auditory system correctly in order to perform efficient and timely feedback monitoring during subsequent speaking. As support to this idea, they reported that speakers experienced a normalization of the neural activation of the auditory system, when an artificial temporal delay was introduced between speech production and auditory feedback (Daliri and Max 2018). Delayed auditory feedback is a condition that is known to reduce stuttering symptoms (Kalinowski et al. 1993). Speakers who stutter tolerate auditory feedback presented as late as 50 ms after the moment of real-time auditory feedback without disturbing the actual speaking process (Kalinowski et al. 1993). Interestingly, speakers who do not stutter cannot cope with such a temporal delay and usually strongly struggle with fluency under similar conditions (Davis and Brajot 2019). One explanation for the phenomenon is that the feedforward information provided by the motor system to the auditory system (i.e. the information on how and especially *when* a syllable should be heard which is generated by an internal model during speech planning) might be fuzzy or erroneous in speakers who stutter. Hence, people who stutter might benefit from a delay that gives them more time to match feedforward and actual feedback information.

This latter account was further developed by Harrington (1988). He emphasized the potential role of rhythmic structure and erroneous temporal predictions for stuttering. Specifically, he proposed that the temporal expectancies for the moment of perception of a rhythmically important event (e.g. the vowel sound of a syllable) would not match with its actual moment of production. In other words, the information about speech motor timing communicated between the motor system and the auditory system may be temporally mis-aligned. Some evidence for this idea comes from a study of Etchell et al. (2016) who found a delayed response of cortical oscillatory activity related to temporal prediction of rhythmic non-verbal events (i.e. tones) in the auditory cortex in children who stutter compared to children who do not stutter. Studying oscillatory neural activity might also open a window to better understand the nature of temporal predictions in stuttering in the future (e.g. Etchell et al. 2014; Kikuchi et al. 2017).

In sum, the current literature supports the idea that altered timing in motor control plays a central role in stuttering. Current results point towards temporal mis-alignments between predicted and perceived speech events during speech production. This misalignment could hinder timely sensorimotor integration leading to problems with speech initiation and thereby causing stuttering symptoms. Although most of the available research is centred on speech-specific mechanisms and models, it is not excluded that more general aspects of temporal motor control are involved (see the following sections). Note, however, that it remains still an open question whether observed altered timing processes are the origin of stuttering or rather reflect compensatory strategies or mechanisms in people who stutter.

2.3 Brain correlates of stuttering: sensorimotor and timing resources

The neurosciences of stuttering have made tremendous progress since the beginning of the new millennium. Research shows that developmental stuttering originates from a neurodiverse brain maturation which displays altered structural and functional differences and/or unbalanced neurotransmission in the brain. The pathways pointed out are in particular those connecting cortical areas (including (pre-)supplementary motor cortex, inferior frontal gyrus) to subcortical structures, in particular, the basal ganglia and the thalamus (i.e. the cortico-basal ganglia-thalamo-cortical circuit, henceforth BGTC; Alm 2004, 2021; Chang et al. 2019; Chang and Guenther 2020). Weakness in BGTC connectivity and/or neurotransmission is likely to cause the untimely initiation and inhibition of speech motor programmes (e.g. Civier et al. 2013; Metzger et al. 2018). Importantly, this network is also known for its eminent role in motor timing and rhythmic processing in other domains than speech such as music (Cannon and Patel 2021; Henry et al. 2017; Nozaradan et al. 2017; Rao et al. 1997). Another timing network relevant for music processing seems more active in people who stutter than in people who do not stutter, that is, the cerebellar-thalamo-cortical pathway (Frankford et al. 2021; Johnson et al. 2022). This pathway is particularly involved with external timing tasks such as synchronizing to a metronome beat or music in general and functions as a complementary timing network together with the BGTC in speech (Ackermann 2008; Christensen et al. 2014).

Moreover, speakers who stutter show many differences in brain structure, connectivity, and activation, particularly in regions relevant for sensorimotor processes and for the left-dominant speech production system, compared to people who do not stutter. One region under particular scrutiny is the inferior frontal gyrus, a hub for general motor-related brain networks as well as heavily involved in the motor programming of speech (e.g. Neef et al. 2016). Cerebral blood flow was found to be reduced in this region (Desai et al. 2017) and grey matter maturation across the lifespan is different from speakers who do not stutter (Beal et al. 2015; Thompson-Lake et al. 2022). Furthermore, neuroimaging studies report weaker connections between left frontal motor sequencing and planning areas (e.g. inferior frontal gyrus towards (pre-)SMA via the frontal aslant tract; Kemerdere et al. 2016). Weaker connections were also observed between areas sustaining sensorimotor information flow in the speech production network such as left auditory and motor areas (temporal to frontal cortices, e.g. Kronfeld-Duenias et al. 2016; Neef et al. 2015; as well as fronto-parietal connections, Benito-Aragón et al. 2020; Neef et al. 2016). Activation of the left auditory cortex was also reduced in stuttering (Connally et al. 2018).

As in many other neurodevelopmental speech disorders, right hemisphere areas (e.g. right IFG) tend to show unusual activation in adults who stutter (e.g. Kell et al. 2009), suggesting right-hemisphere compensatory mechanisms coming with the experience of stuttering. Stronger connections and hyperactivity in right-hemisphere networks triggering inhibition of motor responses are predictive of stuttering severity (e.g. right inferior gyrus, frontal aslant tract; Neef et al. 2018). Normalization in this network is also related to socio-emotional therapy outcomes (Neef et al. 2022).

Another neural marker of altered processes in the brain of speakers who stutter is the time course of oscillatory neural activity, particularly the modulation in the beta-band (see Korzeczek et al. 2022, for an overview). Beta-band modulation is particularly relevant for setting up the speech production system, and for processing feedforward information. Hence, beta-band activity indicates how reliable the sensorimotor network may function during speech production. Significant beta-band activity differences to speakers who do not stutter were found in the mouth motor cortices before and during speaking (e.g. Mersov et al. 2016), in the left sensorimotor cortex (Bowers and Hudock 2024) as well as in auditory cortices of speakers who stutter (e.g. Etchell et al. 2016). Moreover, recruitment of left and right motor and auditory cortices during speaking show some differences and delays in oscillatory activity in speakers who stutter, but not in speakers who do not stutter (Kikuchi et al. 2017; Mersov et al. 2016; Salmelin et al. 2000).

To summarize, the neuroscience of stuttering is a highly dynamic research area producing evidence that points to characteristic differences in general and speech-related sensorimotor neural resources and processes as well as in the general rhythm and timing network in speakers who do and do not stutter. This growing knowledge open exciting new insights into how the brain enables us to perform complex human rhythmic motor actions in speech as well as in music.

3 Music and stuttering

Stuttering is viewed as a condition affecting primarily oral speech and communication. Only a few (mostly case) studies evoke the possibility that people who stutter may experience stuttering-like dysfluencies during non-verbal communication, e.g. while playing a musical instrument (Silverman and Bohlman 1988; van Riper 1982) or in sign language (Cosyns et al. 2009; Silverman and Silverman 1971). On the contrary, music seems to ease the burden of experiencing stuttering symptoms. Speakers who stutter can sing without displaying overt stuttering symptoms (see Falk et al. 2020, for an overview) and other fluency-enhancing conditions such as choral speech or speaking with a metronome have important musical components. Nevertheless, music or musical capacities were so far only a marginal topic in research on stuttering. With the advent of a research line on a potential link between language and music in neurodevelopmental disorders (e.g. Boorom et al., this volume; Fiveash et al. 2021; Patel 2010) and the potential effect of stuttering on general motor control timing, the question of musical capacities in stuttering (section 3.2) and the impact of musical training (section 3.3) may become of broader interest.

3.1 Fluency-enhancing musical activities

Stuttering symptoms can almost disappear when speakers who stutter engage in musical *vocal* activities. While singing, stuttering symptoms may drop by 90 per cent compared to speaking (Andrews et al. 1982; Glover et al. 1996), combined with lesser inner anticipation of stuttering (van de Vorst 2020). Similar percentages in reduction of overt stuttering symptoms are found when people who stutter speak along with a metronome or participate in chorus reading, together with a partner (e.g. reading a text simultaneously; Andrews et al. 1982). Critically, these effects are temporary, and wane immediately when switching back to self-paced and -initiated spoken speech. Furthermore, although these conditions reduce stuttering-typical dysfluencies, they do not remove some of the critical articulatory and neural differences in speech production between speakers who do and do not stutter. For example, even while singing, adolescents who stutter display higher durational variability at the segmental and utterance level than peers who do not stutter (Falk et al. 2015). Motor preparation shows similar differences to a control group in neural activation for humming than speaking in a group of adults who stutter (Neef et al. 2016). During fluency-enhancing choral speech, adults who stutter show higher temporal variability than a group without stuttering (Zhu et al. 2025; but see Assaneo et al. 2022 for a more detailed view on individual profiles in a large sample). They also show neural activation patterns typical of stuttering in this condition (Garnett et al. 2022).

These findings underline the need for a better understanding of (permanent) traits and (time-varying) states in the study of stuttering (Belyk et al. 2015; Connally et al. 2018). Fluency-enhancing musical activities are an interesting area of research, as they may help unravelling potential sources of fluency states. The most prominent hypothesis is that fluency-enhancing musical activities result in more effective auditory-motor coupling during speech production (Garnett et al. 2022; Stager et al. 2003). Better auditory-motor processing may improve auditory self-monitoring (Stager et al. 2003) as well as foster rhythmic predictions through internal (singing) or external (metronome, another person's speech) rhythms which may ultimately help better motor coordination (Falk et al. 2015, 2016). From a neural perspective, research underlines the importance of normalization of basal ganglia activity during rhythmic processing and better functioning of the BGTC circuit (Toyomura et al. 2011, 2015). Finally, reduced pressure for communication and online speech processing may also result in improved stuttering management (e.g. read texts, highly familiar lyrics, etc.; Healey et al. 1976).

Fluency-enhancing musical activities are not an integral part of speech therapy. They are sometimes used to make clients aware of the variability of fluency and of the fact that they actually *are* able to speak or sing without stuttering. Some aspects of fluency-enhancing musical activities overlap with training programmes using articulatory techniques: e.g. prolonging vowels, using smooth onsets or controlling breathing, and pausing patterns are techniques used in therapy as well as in singing. Pacing devices, creating a situation of choral speech while speaking, have been used for a while in commercial products to reduce stuttering symptoms—with mixed results, especially concerning the durability of the effect and displaying high individual variability (e.g. Pollard et al. 2009). Currently, research is ongoing to examine whether training based on metronome-paced speech paired with concurrent neuromodulation (i.e. transcranial direct current stimulation) may be an avenue for improving fluency management in adults (Chesters et al. 2018).

3.2 Musical abilities and stuttering

Although some musical conditions such as singing can improve some aspects of stuttering, stuttering also seems to impact some non-verbal musical capacities, especially in the domain of rhythm. Several studies reported on alterations in non-verbal rhythm and timing abilities in children and adults who stutter, although results are not always replicated. Some studies observed reduced speed, accuracy, and retention of learning sequences of finger taps in adults who stutter (Smits-Bandstra and de Nil 2007, for an overview; but see Korzeczek et al. 2020 for different results). Toyomura and colleagues (2021) found slower/less accurate patterns in complex bimanual finger tapping coordination. They therefore proposed that motor timing tasks (at least with upper limb movements) that require a high ability in motor control and motor skill learning may be challenging for individuals who stutter. As for rhythmic abilities, Falk et al. (2015) reported different timing patterns in finger tapping with musical sounds in children and adolescents who stutter (9–17 years). 65 per cent of a group of 20 children and adolescents showed either more variability or lesser accuracy or both when synchronizing finger taps to a metronome or music. In particular, independently of age, tap timing accuracy was different. Children who stutter tapped around ~20–30 ms earlier in relation to the musical beat than children who did not stutter. This slight but consistent timing difference was also found in a group of 14 adults who stutter by Sares et al. (2019), who tested synchronization to a metronome. (A similar result was found by van de Vorst and Gracco (2017) (N = 11) and Slis et al. (2023) (N = 16), however, another study with adults failed to find group differences (Max and Yudman 2003).) The group of adults from Sares et al. (2019) underwent neuroimaging to determine potential differences in white matter connectivity sustaining sensorimotor synchronization in adults who stutter (Jossinger et al. 2022). Interestingly, in control participants, but not in adults who stutter, more synchronous tap timing to the beat was associated with better connectivity of the left arcuate fasciculus, a white matter structure that is known for relating auditory and motor representations of sound. In addition, participants who stutter showed a correlation of their tap timing with the connectivity of left inferior cerebellar peduncles, suggesting that error monitoring and/or auditory-motor integration might be controlled by different brain networks in people who do and do not stutter (see Frankford et al. 2021; Johnson et al. 2022; and Jossinger et al. 2021 on further results on cerebellar structure and (speech) motor control in people who stutter).

Finally, Wieland et al. (2015) had children who do and do not stutter compare different rhythmic tonal patterns in order to test their rhythm discrimination abilities. The 17 children who stutter performed less well in the discrimination task. Moreover, while children who do not stutter showed a relation between rhythm discrimination and the connectivity of the brain rhythm network (i.e. the left putamen with the bilateral motor and auditory areas and the cerebellum), children who stutter did not show this relation (Chang et al. 2016). The authors propose that these perceptual results in combination with the neural results indicate that children who stutter may have problems in generating an internal beat, a capacity that might be equally relevant for music and speech perception and production (see Kotz and Schwartze 2010, for a model).

Although small in number and participants, these results point towards some alterations of non-verbal rhythm perception and production in people who stutter. Note, however, that the reported differences with speakers who do not stutter were rather small and might be barely noticeable by a naive observer. In addition, future research should more explore the individual variability of non-verbal (see e.g. Falk et al. 2015), but also verbal aspects of stuttering—a general need in the research on neurodevelopmental disorders.

To summarize the last two sections (section 3.1), musical activities *combined* with speech like singing or speaking rhythmically are among the most powerful fluency-enhancing conditions in people who stutter. On the other hand (section 3.2), we observe musical and motor rhythm peculiarities beyond speech in speakers who stutter. Although this seems contradictory, both phenomena could be just opposite sides of the same coin. That is, musical alterations, although small, could testify that networks sustaining general timing and auditory-motor coupling in complex motor behaviour are altered in stuttering. Fluency effects through musical enhancement, on the other hand, could result from the fact that music fosters auditory-motor integration and/or provides more predictable temporal anchors than speech alone (e.g. via highly regular beat structure) and thereby facilitates the generation of prospective temporal patterns, a mechanism supposed to be error-prone in speakers who stutter (Chang et al. 2016; Falk et al. 2015; Harrington 1988).

3.3 Long-term musical training and stuttering

3.3.1 Stuttering in professional musicians

Besides immediate effects on fluency, musical activities have emotional and expressive benefits for the performer. Performing music on a regular basis may help overcome negative feelings, help self-expression, and enhance well-being and social participation in people who stutter, as it does in other people with and without speech and communication disorders (Boster et al. 2021; Good and Russo 2022; Kreutz et al. 2004). As no study to date reports on these effects in people who stutter, the next section will briefly explore some testimonies from professional musicians who stutter as well as what is known about long-term musical training in people who stutter.

Several famous musicians who stutter are singer-songwriters or rappers. Some of them emphasize the value of singing as an alternative way of vocal expression to speaking. For example, Australian Jazz-singer Megan Washington testified in 2014 (TEDx Talk) that singing, for her, was a way of treatment when she was young, as singing was the only way to make her feel in control over her speech. Similarly, famous country-singer Melvin Tillis and hip-hop star Kendrick Lamar were drawn to singing and rapping as it was a way for them to express their thoughts (Lamar), in front of others (Tillis) without having to speak and to stutter (Bonman 2014; Burns 2019). Some musicians think that intensive musical training as a child has helped them to speed up recovery from stuttering. In a speech given at the American Institute for Stuttering (8 June 2015), British popstar Ed Sheeran said that he learned to rap at 9 years of age and that he believes that intensive rapping and its rhythmical properties had helped him to overcome his stuttering. From yet another point of view, the experience of stuttering was reported to aid musical expression and performance. American Jazz-musician and famous scat-singer John Larkin (also known as the 'Scatman') revealed in an interview that stuttering helped him to learn how to scat (Schäfers et al. 1995). He conveyed the idea that the way a syllable is interrupted and repeated during stuttering resembles and could be transformed into an artistic form of scat-song. Furthermore, pointing to benefits of multimodal auditory-motor practice, he said that singing the notes while playing them on the piano helped him gain speed and to play and sing very fast. Another interesting insight comes from pianist, researcher, and person who stutters, Robert van de Vorst (van de Vorst 2013). He proposes that for both, speech and piano performance, a 'musical image' or 'singing sound' providing an idea how a sound or tone continues and connects to the musical or spoken sequence might help fluency. Therefore, learning to convey the overarching flow could be a strategy to gain in expressive fluency in both speech and music performance.

3.3.2 Relation between musical training and stuttering severity

So far, it is an open question whether long-term musical training affects stuttering and speech motor processes in a significant way. We know that professional musicians like Melvin Tillis and Megan Washington, but also Elvis Presley or Kylie Minogue, continued to stutter despite long-term musical training and performance. Still there might be some improvement coming from musical training (see section 3.4 below) that affects stuttering severity. In a study with 14 adults who stutter (not professional musicians), Sares et al. (2019) observed that more musical training over the years was related to lower self-rated stuttering severity. Preliminary data from our own lab suggest that musical training may generate some positive effect on stuttering severity in children. In a sample of 48 children who stutter between the ages of 9 and 17, tested in the Munich area (Germany), we found significantly higher scores in stuttering severity (SSI-3; Riley 2009) in children without any musical training compared to children who had some (1–3 years) or more (> 3 years) musical experience. The difference amounted to severe stuttering scores on average in children without musical training vs. moderate severity scores in children with musical training. These data give promising directions for future research with both children and adults who stutter.

3.3.3 Potential of musical training for stuttering intervention

To our knowledge, Fujii and Wan (2014) were the first to discuss the potential of musical training for speakers who stutter. Their argument is based on the idea that weaker neural connections with the basal ganglia in speakers who stutter might be trained via musical tasks, such as sensorimotor synchronization to a beat or pulse. However, no musical training study with participants who stutter has since been conducted. Based on the previous overview, one might go further and emit the following hypotheses about how musical training might help improve different aspects of stuttering and could serve as a potential complementary tool in stuttering intervention.

Sensorimotor effects and fluency

Musical performance is particularly efficient to train auditory acuity (Patel et al. 2009; see also Elmer and Besson, this volume), and potentially, general motor stability, that is, the consistence in movement performance over repetitions. Both aspects are related to better auditory feedback control in speech (Brunner et al. 2011; Oschkinat et al. 2022). Hence, there is the possibility that musical training might improve auditory self-monitoring as well as motor stability in speakers who stutter, both domains in which people who stutter have shown weaknesses. In line with Fuji and Wan's (2014) idea, rhythmic training is a particularly promising avenue to produce sensorimotor transfer effects from music to *temporal* speech motor control (Dalla Bella 2022). A pilot study with patients with Parkinson's disease from Puyjarinet et al. (2022) found that intensive rhythm training via a tablet game that consists in tapping to the musical beat (Bégel et al. 2018) not only improved manual rhythmic capacities but also orofacial coordination. Potential improvements in temporal (speech) motor control could result in several effects: there could be a direct reduction of stuttering events, and/or a better coping with the unpredictable variability of stuttering. Or the effect could be more indirect and musical training could help speakers who stutter to better learn and use motor strategies and therapeutic techniques to control their stuttering. Another question to explore is whether musical training could produce better results in children and adolescents who stutter than in adults, because of higher chances of spontaneous remissions and generally higher neuroplasticity and higher malleability of neural and motor processes during development.

Socio-emotional aspects

As discussed elsewhere in this volume (Sihvonen et al., this volume), musical performance and training might affect different dimensions of well-being in people who stutter. However, one would expect that these effects may be unspecific to stuttering but apply to all individuals with and even without communication disorders. Musical practice could positively impact stress level and body tension, reduce anxiety and self-stigmatization, lead to higher self-awareness and self-esteem, foster self-expression and empowerment, and evoke positive emotions and higher resilience in difficult situations (e.g. Bullack et al. 2018; Good and Russo 2022).

Communicative effects

Via sensorimotor improvements and better timing capacities, musical training could also impact communicative capacities. The smooth flow of dyadic conversation relies on predictions about what our interlocutor is going to say and when (e.g. Pickering and Gambi 2018). Listeners generate predictions about upcoming content at all linguistic levels (sound, structure, meaning, and intention) to plan their own contributions (e.g. Pickering and Garrod 2007). Some theoretical models propose that the most effective mechanism to generate predictions is to use the own production system during comprehension to simulate what the other interlocutor is saying (e.g. Hickok and Poeppel 2007; Pickering and Garrod 2013). However, because their differences in speech production and particularly because of the interruptions due to stuttering, speakers who stutter and their interlocutors might have difficulties with each other to predict and coordinate their contributions in time (i.e. turn-taking). Musical training and associated sensorimotor and timing improvement might help people who stutter to better coordinate with their interlocutors. In particular, group music settings (such as in choirs or orchestra) might enhance better inter-personal coordination and timing skills. Future research could address the question whether musical training (solo, dyadic, or in a group) may affect speech timing in conversation between participants who do and do not stutter (turn taking, interpersonal rhythmic adaptation, coping strategies).

4 Summary

The role that music plays in stuttering, a neuro-developmental motor speech and communication disorder, is to date widely unknown. This chapter advocates, however, that studying music and stuttering promises to be of importance for our general understanding of the underlying links between speech and music capacities, at the developmental and the neural level. The existing evidence reviewed here suggests that musical activities can impact stuttering and its symptoms. It has been known for a while, that combining speech with musical components such as singing, speaking with an external beat or choral speech can significantly reduce the amount of disfluencies in speech production, and eases the burden of the unpredictability of stuttering. From a scientific standpoint, these effects might derive from better self-monitoring, auditory-motor coupling, and generally better temporal motor control during these activities as can also been seen in higher activation of certain neural circuits. Results also showed mild to moderately altered non-verbal rhythmic capacities in the perception and production of music in individuals who stutter. These findings hint to the alteration of a larger, non-speech specific timing system in stuttering. In the future, it will be important to investigate the neural resources underlying this timing system and its role for speech as well as for music production. To achieve this, stuttering should be considered among other neuro-developmental speech and language disorders (Aichert and Ziegler, this volume) that show altered non-verbal timing. Furthermore, preliminary results and testimonies of some achieved musicians who stutter suggest that musical training might provide positive outcomes for the management of stuttering and its socio-emotional impact, at least for a sub-group of individuals. Future studies could address the question whether we can observe transfer effects from long-term or intensive musical training on different speech-related and communicative aspects of stuttering, as well as individual traits of responding participants. A therapeutic value of music for stuttering, however, remains by now unsubstantiated, as stuttering therapy has first and foremost the aim to provide individuals with ways to relieve from the sometimes heavy communicative and psychological consequences of stuttering. Nevertheless, people who stutter could benefit from musical activities, like other individuals with communication disorders, in terms of group participation, self-expression, pleasure, emotional and bio-physiological well-being, as well as a means of self-empowerment.

References

Ackermann, H. (2008), 'Cerebellar Contributions to Speech Production and Speech Perception: Psycholinguistic and Neurobiological Perspectives', *Trends in Neurosciences*, 31/6, 265–272, https://doi.org/10.1016/j.tins.2008.02.011.
Google Scholar WorldCat

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.
Google Scholar WorldCat

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, Article 661880, https://doi.org/10.3389/fnhum.2021.661880.
Google Scholar WorldCat

American Institute for Stuttering (2015), 'Ed Sheeran Speaks at the 2015 American Institute for Stuttering Gala' [Video], June 12, https://www.youtube.com/watch?v=K_3r3SolyDs.
WorldCat

American Psychiatric Association (2013), *Diagnostic and Statistical Manual of Mental Disorders: DSM*-5, 5th ed. (Washington, DC: American Psychiatric Publishing).

American Speech-Language-Hearing Association (n.d.), 'Stuttering', Retrieved October 28, 2022, from https://www.asha.org/public/speech/disorders/stuttering/.
WorldCat

Andrews, G., Howie, P. M., Dozsa, M., and Guitar, B. E. (1982), 'Stuttering', *Journal of Speech, Language, and Hearing Research*, 25/2, 208–216, https://doi.org/10.1044/jshr.2502.208.
Google Scholar WorldCat

Assaneo, M. F., Ripollés, P., Tichenor, S. E., Yaruss, J. S., and Jackson, E. S. (2022), 'The Relationship Between Auditory-Motor Integration, Interoceptive Awareness, and Self-Reported Stuttering Severity,' *Frontiers in Integrative Neuroscience*, 16, Article 869571, https://doi.org/10.3389/fnint.2022.869571.
Google Scholar WorldCat

Beal, D. S., Lerch, J. P., Cameron, B., Henderson, R., Gracco, V. L., and 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, Article 89, https://doi.org/10.3389/fnhum.2015.00089.
Google Scholar WorldCat

Bégel, V., Seilles, A., and Dalla Bella, S. (2018), 'Rhythm Workers: A Music-Based Serious Game for Training Rhythm Skills', *Music and Science*, 1, 1–16, https://doi.org/10.1177/2059204318794369.
Google Scholar WorldCat

Belyk, M., Kraft, S. J., and Brown, S. (2015), 'Stuttering as a Trait or State—An ALE Meta-analysis of Neuroimaging Studies', *European Journal of Neuroscience*, 41/2, 275–284, https://doi.org/10.1111/ejn.12765.
Google Scholar WorldCat

Benito-Aragón, C., Gonzalez-Sarmiento, R., Liddell, T., Diez, I., d'Oleire Uquillas, F., Ortiz-Terán, L., Bueichekú, E., Chow, H. M., Chang, S.-E., and Sepulcre, J. (2020), 'Neurofilament-Lysosomal Genetic Intersections in the Cortical Network of Stuttering', *Progress in Neurobiology*, 184, Article 101718, https://doi.org/10.1016/j.pneurobio.2019.101718.
Google Scholar WorldCat

Bloodstein, O., and Bernstein Ratner, N. (2008), *A Handbook on Stuttering*, 6th ed. (Clifton Park, NY: Thomson Delmar Learning).
Google Scholar Google Preview WorldCat COPAC

Bonman, L. (2014), 'Kendrick Lamar, Hip-Hop's Newest Old-School Star', *New York Times*, June 25.

Boster, J. B., Spitzley, A. M., Castle, T. W., Jewell, A. R., Corso, C. L., and McCarthy, J. W. (2021), 'Music Improves Social and Participation Outcomes for Individuals with Communication Disorders: A Systematic Review', *Journal of Music Therapy*, 58/1, 12–42, https://doi.org/10.1093/jmt/thaa015.
Google Scholar WorldCat

Bowers, A., and Hudock, D. (2024), 'Reduced Resting-State Periodic Beta Power in Adults Who Stutter Is Related to Sensorimotor Control of Speech Execution,' *Cortex*, 181, 74–92, https://doi.org/10.1016/j.cortex.2024.09.016.
Google Scholar WorldCat

Briley, P. M., and Ellis, C. (2018), 'The Coexistence of Disabling Conditions in Children Who Stutter: Evidence from the National Health Interview Survey', *Journal of Speech, Language, and Hearing Research*, 61/12, 2895–2905, https://doi.org/10.1044/2018_JSLHR-S-17-0378.
Google Scholar WorldCat

Brunner, J., Ghosh, S., Hoole, P., Matthies, M., Tiede, M., and Perkell, J. (2011), 'The Influence of Auditory Acuity on Acoustic Variability and the Use of Motor Equivalence During Adaptation to a Perturbation', *Journal of Speech, Language, and Hearing Research*, 54/3, 727–739, https://doi.org/10.1044/1092-4388(2010/09-0256).
Google Scholar WorldCat

Bullack, A., Gass, C., Nater, U. M., and Kreutz, G. (2018), 'Psychobiological Effects of Choral Singing on Affective State, Social Connectedness, and Stress: Influences of Singing Activity and Time Course', *Frontiers in Behavioral Neuroscience*, 12, Article 223, https://doi.org/10.3389/fnbeh.2018.00223.
Google Scholar WorldCat

Burns, K. (2019), '*Mel Tillis: Learning to Talk through Singing' [Video],* September 15. PBS, https://www.pbs.org/video/ken-burns-country-music-episode-4-i-cant-stop-loving-you-mel-tillis-learning-talk-through-singing-gcboiz/.
Google Scholar Google Preview WorldCat COPAC

Cai, S., Beal, D. S., Ghosh, S. S., Guenther, F. H., and Perkell, J. S. (2014), 'Impaired Timing Adjustments in Response to Time-Varying Auditory Perturbation during Connected Speech Production in Persons Who Stutter', *Brain and Language*, 129, 24–29, https://doi.org/10.1016/j.bandl.2014.01.002.
Google Scholar WorldCat

Cai, S., Beal, D. S., Ghosh, S. S., Tiede, M. K., Guenther, F. H., and Perkell, J. S. (2012), 'Weak Responses to Auditory Feedback Perturbation during Articulation in Persons Who Stutter: Evidence for Abnormal Auditory-Motor Transformation', *Plos One*, 7/7, Article e41830, https://doi.org/10.1371/journal.pone.0041830.
Google Scholar WorldCat

Cannon, J. J., and Patel, A. D. (2021), 'How Beat Perception Co-opts Motor Neurophysiology', *Trends in Cognitive Sciences*, 25/2, 137–150, https://doi.org/10.1016/j.tics.2020.11.002.
Google Scholar WorldCat

Chang, S.-E., Garnett, E. O., Etchell, A., and Chow, H. M. (2019), 'Functional and Neuroanatomical Bases of Developmental Stuttering: Current Insights', *The Neuroscientist*, 25/6, 566–582, https://doi.org/10.1177/1073858418803594.
Google Scholar WorldCat

Chang, S.-E., and Guenther, F. H. (2020), 'Involvement of the Cortico-Basal Ganglia-Thalamocortical Loop in Developmental Stuttering', *Frontiers in Psychology*, 10, Article 3088, https://doi.org/10.3389/fpsyg.2019.03088.
Google Scholar WorldCat

Chang, S. E., Chow, H. M., Wieland, E. A., and McAuley, J. D. (2016), 'Relation between Functional Connectivity and Rhythm Discrimination in Children Who Do and Do Not Stutter', *Neuroimage-Clinical*, 12, 442–450, https://doi.org/10.1016/j.nicl.2016.08.021.

Google Scholar WorldCat

Chesters, J., Möttönen, R., and Watkins, K. E. (2018), ‘Transcranial Direct Current Stimulation over Left Inferior Frontal Cortex Improves Speech Fluency in Adults Who Stutter’, *Brain*, 141/4, 1161–1171, https://doi.org/10.1093/brain/awy011.
Google Scholar WorldCat

Choo, A. L., Smith, S. A., and Li, H. (2020), ‘Associations between Stuttering, Comorbid Conditions and Executive Function in Children: A Population-Based Study’, *BMC Psychology*, 8/1, Article 113, https://doi.org/10.1186/s40359-020-00481-7.
Google Scholar WorldCat

Christensen, A., Giese, M. A., Sultan, F., Mueller, O. M., Goericke, S. L., Ilg, W., and Timmann, D. (2014), ‘An Intact Action-Perception Coupling Depends on the Integrity of the Cerebellum’, *Journal of Neuroscience*, 34/19, 6707–6716, https://doi.org/10.1523/jneurosci.3276-13.2014.
Google Scholar WorldCat

Civier, O., Bullock, D., Max, L., and 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.
Google Scholar WorldCat

Civier, O., Tasko, S. M., and Guenther, F. H. (2010), ‘Overreliance on Auditory Feedback May Lead to Sound/Syllable Repetitions: Simulations of Stuttering and Fluency-Inducing Conditions with a Neural Model of Speech Production’, *Journal of Fluency Disorders*, 35/3, 246–279, https://doi.org/10.1016/j.jfludis.2010.05.002.
Google Scholar WorldCat

Connally, E. L., Ward, D., Pliatsikas, C., Finnegan, S., Jenkinson, M., Boyles, R., and 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.
Google Scholar WorldCat

Cosyns, M., Van Herreweghe, A., Christiaens, G., and Van Borsel, J. (2009), ‘Stutter-Like Dysfluencies in Flemish Sign Language Users’, *Clinical Linguistics and Phonetics*, 23/10, 742–750, https://doi.org/10.3109/02699200903090015.
Google Scholar WorldCat

Daliri, A., and Max, L. (2015a), ‘Electrophysiological Evidence for a General Auditory Prediction Deficit in Adults Who Stutter’, *Brain and Language*, 150, 37–44, https://doi.org/https://doi.org/10.1016/j.bandl.2015.08.008.
Google Scholar WorldCat

Daliri, A., and Max, L. (2015b), ‘Modulation of Auditory Processing during Speech Movement Planning Is Limited in Adults Who Stutter’, *Brain and Language*, 143, 59–68, https://doi.org/10.1016/j.bandl.2015.03.002.
Google Scholar WorldCat

Daliri, A., and Max, L. (2018), ‘Stuttering Adults’ Lack of Pre-speech Auditory Modulation Normalizes When Speaking with Delayed Auditory Feedback’, *Cortex*, 99, 55–68, https://doi.org/10.1016/j.cortex.2017.10.019.
Google Scholar WorldCat

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.
Google Scholar WorldCat

Davis, S. N., and Brajot, F.-X. (2019), ‘Partial Compensation to Delayed Auditory Feedback: An Analysis of Syllable Duration’, *Journal of the Acoustical Society of America*, 145/6, 3531–3540, https://doi.org/10.1121/1.5111758.
Google Scholar WorldCat

de Sonneville-Koedoot, C., Stolk, E., Rietveld, T., and Franken, M.-C. (2015), ‘Direct versus Indirect Treatment for Preschool Children Who Stutter: The RESTART Randomized Trial’, *Plos One*, 10/7, Article e0133758,

https://doi.org/10.1371/journal.pone.0133758.
Google Scholar WorldCat

Desai, J., Huo, Y., Wang, Z., Bansal, R., Williams, S. C. R., Lythgoe, D., Zelaya, F. O., and Peterson, B. S. (2017), 'Reduced Perfusion in Broca's Area in Developmental Stuttering', *Human Brain Mapping*, 38/4, 1865–1874, https://doi.org/10.1002/hbm.23487.
Google Scholar WorldCat

Etchell, A. C., Johnson, B. W., and Sowman, P. F. (2014), 'Behavioral and Multimodal Neuroimaging Evidence for a Deficit in Brain Timing Networks in Stuttering: A Hypothesis and Theory', *Frontiers in Human Neuroscience*, 8, Article 467, https://doi.org/10.3389/fnhum.2014.00467.
Google Scholar WorldCat

Etchell, A. C., Ryan, M., Martin, E., Johnson, B. W., and Sowman, P. F. (2016), 'Abnormal Time Course of Low Beta Modulation in Non-fluent Preschool Children: A Magnetoencephalographic Study of Rhythm Tracking', *Neuroimage*, 125, 953–963, https://doi.org/10.1016/j.neuroimage.2015.10.086.
Google Scholar WorldCat

Falk, S., Maslow, E., Thum, G., and Hoole, P. (2016), 'Temporal Variability in Sung Productions of Adolescents Who Stutter', *Journal of Communication Disorders*, 62, 101–114, https://doi.org/10.1016/j.jcomdis.2016.05.012.
Google Scholar WorldCat

Falk, S., Müller, T., and Dalla Bella, S. (2015), 'Non-verbal Sensorimotor Timing Deficits in Children and Adolescents Who Stutter', *Frontiers in Psychology*, 6, Article 847, https://doi.org/10.3389/fpsyg.2015.00847.
Google Scholar WorldCat

Falk, S., Schreier, R., and Russo, F. A. (2020), 'Singing and Stuttering', in R. Heydon, D. Fancourt, and A. J. Cohen eds, *The Routledge Companion to Interdisciplinary Studies in Singing*, Vol. III: *Wellbeing* (New York: Routledge), 50–60.

Fiveash, A., Bedoin, N., Gordon, R. L., and Tillmann, B. (2021), 'Processing Rhythm in Speech and Music: Shared Mechanisms and Implications for Developmental Speech and Language Disorders', *Neuropsychology*, 35/8, 771–791, https://doi.org/10.1037/neu0000766.
Google Scholar WorldCat

Frankford, S. A., Murray, E. S. H., Masapollo, M., Cai, S., Tourville, J. A., Nieto-Castañón, A., and Guenther, F. H. (2021), 'The Neural Circuitry Underlying the "Rhythm Effect" in Stuttering', *Journal of Speech, Language, and Hearing Research*, 64/6S, 2325–2346, https://doi.org/10.1044/2021_JSLHR-20-00328.
Google Scholar WorldCat

Frigerio-Domingues, C., and Drayna, D. (2017), 'Genetic Contributions to Stuttering: The Current Evidence', *Molecular Genetics and Genomic Medicine*, 5/2, 95–102, https://doi.org/10.1002/mgg3.276.
Google Scholar WorldCat

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

Garnett, E. O., Chow, H. M., Limb, S., Liu, Y., and Chang, S.-E. (2022), 'Neural Activity during Solo and Choral Reading: A Functional Magnetic Resonance Imaging Study of Overt Continuous Speech Production in Adults Who Stutter', *Frontiers in Human Neuroscience*, 16, Article 894676, https://doi.org/10.3389/fnhum.2022.894676.
Google Scholar WorldCat

Glover, H., Kalinowski, J., Rastatter, M., and Stuart, A. (1996), 'Effect of Instruction to Sing on Stuttering Frequency at Normal and Fast Rates', *Perceptual and Motor Skills*, 83/2, 511–522, https://doi.org/10.2466/pms.1996.83.2.511.
Google Scholar WorldCat

Good, A., and Russo, F. A. (2022), 'Changes in Mood, Oxytocin, and Cortisol Following Group and Individual Singing: A Pilot Study', *Psychology of Music*, 50/4, 1340–1347, https://doi.org/10.1177/03057356211042668.
Google Scholar WorldCat

Guitar, B. (2014), *Stuttering: An Integrated Approach to Its Nature and Treatment*, 4th ed. (Philadelphia, PA: Lippincott Williams and Wilkins).
Google Scholar Google Preview WorldCat COPAC

Harrington, J. (1988), 'Stuttering, Delayed Auditory Feedback, and Linguistic Rhythm', *Journal of Speech, Language, and Hearing Research*, 31/1, 36–47, https://doi.org/10.1044/jshr.3101.36.
Google Scholar WorldCat

Healey, E. C., Mallard, A. R., and Adams, M. R. (1976), 'Factors Contributing to the Reduction of Stuttering during Singing', *Journal of Speech and Hearing Research*, 19/3, 475–480, https://doi.org/10.1044/jshr.1903.475.
Google Scholar WorldCat

Henry, K. S., Amburgey, K. N., Abrams, K. S., Idrobo, F., and Carney, L. H. (2017), 'Formant-Frequency Discrimination of Synthesized Vowels in Budgerigars (Melopsittacus undulatus) and Humans', *Journal of the Acoustical Society of America*, 142/4, 2073–2083, https://doi.org/10.1121/1.5006912.
Google Scholar WorldCat

Hickok, G., and Poeppel, D. (2007), 'The Cortical Organization of Speech Processing', *Nature Reviews Neuroscience*, 8/5, 393–402, https://doi.org/10.1038/nrn2113.
Google Scholar WorldCat

Johnson, C. A., Liu, Y., Waller, N., and Chang, S.-E. (2022), 'Tract Profiles of the Cerebellar Peduncles in Children Who Stutter', *Brain Structure and Function*, 227/5, 1773–1787, https://doi.org/10.1007/s00429-022-02471-4.
Google Scholar WorldCat

Jossinger, S., Kronfeld-Duenias, V., Zislis, A., Amir, O., and Ben-Shachar, M. (2021), 'Speech Rate Association with Cerebellar White-Matter Diffusivity in Adults with Persistent Developmental Stuttering', *Brain Structure and Function*, 226, 801–816, https://doi.org/10.1007/s00429-020-02210-7.
Google Scholar WorldCat

Jossinger, S., Sares, A., Zislis, A., Sury, D., Gracco, V., and Ben-Shachar, M. (2022), 'White Matter Correlates of Sensorimotor Synchronization in Persistent Developmental Stuttering', *Journal of Communication Disorders*, 95, Article 106169, https://doi.org/10.1016/j.jcomdis.2021.106169.
Google Scholar WorldCat

Kalinowski, J., Armson, J., Stuart, A., and Gracco, V. L. (1993), 'Effects of Alterations in Auditory Feedback and Speech Rate on Stuttering Frequency', *Language and Speech*, 36/1, 1–16, https://doi.org/10.1177/002383099303600101.
Google Scholar WorldCat

Kell, C. A., Neumann, K., von Kriegstein, K., Posenenske, C., von Gudenberg, A. W., Euler, H., and Giraud, A.-L. (2009), 'How the *Brain* Repairs Stuttering', *Brain*, 132/10, 2747–2760, https://doi.org/10.1093/brain/awp185.

Kemerdere, R., de Champfleur, N. M., Deverdun, J., Cochereau, J., Moritz-Gasser, S., Herbet, G., and Duffau, H. (2016), 'Role of the Left Frontal Aslant Tract in Stuttering: A Brain Stimulation and Tractographic Study', *Journal of Neurology*, 263/1, 157–167, https://doi.org/10.1007/s00415-015-7949-3.
Google Scholar WorldCat

Kikuchi, Y., Okamoto, T., Ogata, K., Hagiwara, K., Umezaki, T., Kenjo, M., Nakagawa, T., and Tobimatsu, S. (2017), 'Abnormal Auditory Synchronization in Stuttering: A Magnetoencephalographic Study', *Hearing Research*, 344, 82–89, https://doi.org/10.1016/j.heares.2016.10.027.

Google Scholar WorldCat

Korzeczek, A., Cholin, J., Jorschick, A., Hewitt, M., and Sommer, M. (2020), 'Finger Sequence Learning in Adults Who Stutter', *Frontiers in Psychology*, 11, Article 1543, https://doi.org/10.3389/fpsyg.2020.01543.
Google Scholar WorldCat

Korzeczek, A., Neef, N. E., Steinmann, I., Paulus, W., and Sommer, M. (2022), 'Stuttering Severity Relates to Frontotemporal Low-Beta Synchronization during Pre-speech Preparation', *Clinical Neurophysiology*, 138, 84–96, https://doi.org/10.1016/j.clinph.2022.03.010.
Google Scholar WorldCat

Kotz, S. A., and Schwartze, M. (2010), 'Cortical Speech Processing Unplugged: A Timely Subcortico-Cortical Framework', *Trends in Cognitive Sciences*, 14/9, 392–399, https://doi.org/10.1016/j.tics.2010.06.005.
Google Scholar WorldCat

Kreutz, G., Bongard, S., Rohrmann, S., Hodapp, V., and Grebe, D. (2004), 'Effects of Choir Singing or Listening on Secretory Immunoglobulin A, Cortisol, and Emotional State', *Journal of Behavioral Medicine*, 27/6, 623–635, https://doi.org/10.1007/s10865-004-0006-9.
Google Scholar WorldCat

Kronfeld-Duenias, V., Amir, O., Ezrati-Vinacour, R., Civier, O., and 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.
Google Scholar WorldCat

Lenneberg, E. H. (1967), *Biological Foundations of Language* (Chichester, UK: John Wiley and Sons).
Google Scholar Google Preview WorldCat COPAC

Max, L., Guenther, F. H., Gracco, V. L., Ghosh, S. S., and 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.
Google Scholar WorldCat

Max, L., and Yudman, E. M. (2003), 'Accuracy and Variability of Isochronous Rhythmic Timing across Motor Systems in Stuttering versus Nonstuttering Individuals', *Journal of Speech, Language, and Hearing Research*, 46/1, 146–163, https://doi.org/10.1044/1092-4388(2003/012).
Google Scholar WorldCat

Mersov, A.-M., Jobst, C., Cheyne, D. O., and De Nil, L. (2016), 'Sensorimotor Oscillations Prior to Speech Onset Reflect Altered Motor Networks in Adults Who Stutter', *Frontiers in Human Neuroscience*, 10, Article 443, https://doi.org/10.3389/fnhum.2016.00443.
Google Scholar WorldCat

Metzger, F. L., Auer, T., Helms, G., Paulus, W., Frahm, J., Sommer, M., and Neef, N. E. (2018), 'Shifted Dynamic Interactions between Subcortical Nuclei and Inferior Frontal Gyri during Response Preparation in Persistent Developmental Stuttering', *Brain Structure and Function*, 223/1, 165–182, https://doi.org/10.1007/s00429-017-1476-1.
Google Scholar WorldCat

Millard, S. K., Zebrowski, P., and Kelman, E. (2018), 'Palin Parent–Child Interaction Therapy: The Bigger Picture', *American Journal of Speech-Language Pathology*, 27/3S, 1211–1223, https://doi.org/10.1044/2018_AJSLP-ODC11-17-0199.
Google Scholar WorldCat

Neef, N. E., Anwander, A., Bütfering, C., Schmidt-Samoa, C., Friederici, A. D., Paulus, W., and Sommer, M. (2018), 'Structural Connectivity of Right Frontal Hyperactive Areas Scales with Stuttering Severity', *Brain*, 141/1, 191–204, https://doi.org/10.1093/brain/awx316.
Google Scholar WorldCat

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

Neef, N. E., Bütfering, C., Anwander, A., Friederici, A. D., Paulus, W., and Sommer, M. (2016), 'Left Posterior-Dorsal Area 44 Couples with Parietal Areas to Promote Speech Fluency, While Right Area 44 Activity Promotes the Stopping of Motor Responses', *Neuroimage*, 142, 628–644, https://doi.org/10.1016/j.neuroimage.2016.08.030.
Google Scholar WorldCat

Neef, N. E., Korzeczek, A., Primaßin, A., Wolff von Gudenberg, A., Dechent, P., Riedel, C. H., Paulus, W., and Sommer, M. (2022), 'White Matter Tract Strength Correlates with Therapy Outcome in Persistent Developmental Stuttering', *Human Brain Mapping*, 43/11, 3357–3374, https://doi.org/10.1002/hbm.25853.
Google Scholar WorldCat

Nozaradan, S., Schwartze, M., Obermeier, C., and Kotz, S. A. (2017), 'Specific Contributions of Basal Ganglia and Cerebellum to the Neural Tracking of Rhythm', *Cortex*, 95, 156–168, https://doi.org/10.1016/j.cortex.2017.08.015.
Google Scholar WorldCat

O'Brian, S., Onslow, M., Cream, A., and Packman, A. (2003), 'The Camperdown Program: Outcomes of a New Prolonged-Speech Treatment Model', *Journal of Speech Language and Hearing Research*, 46/4, 933–946, https://doi.org/10.1044/1092-4388(2003/073).
Google Scholar WorldCat

Onslow, M., Packman, A., and Harrison, E., eds (2003), *The Lidcombe Program of Early Stuttering Intervention: A Clinician's Guide* (Austin, TX: Pro-Ed).
Google Scholar Google Preview WorldCat COPAC

Oschkinat, M., Hoole, P., Falk, S., and Dalla Bella, S. (2022), 'Temporal Malleability to Auditory Feedback Perturbation Is Modulated by Rhythmic Abilities and Auditory Acuity', *Frontiers in Human Neuroscience*, 16, Article 885074, https://doi.org/10.3389/fnhum.2022.885074.
Google Scholar WorldCat

Patel, A. D. (2010), *Music, Language, and the Brain* (Oxford: Oxford University Press).

Patel, A. D., Iversen, J. R., Bregman, M. R., and Schuiz, I. (2009), 'Experimental Evidence for Synchronization to a Musical Beat in a Nonhuman Animal', *Current Biology*, 19/10, 827–830, https://doi.org/10.1016/j.cub.2009.03.038.
Google Scholar WorldCat

Pickering, M. J., and Gambi, C. (2018), 'Predicting While Comprehending Language: A Theory and Review', *Psychological Bulletin*, 144/10, 1002–1044, https://doi.org/10.1037/bul0000158.
Google Scholar WorldCat

Pickering, M. J., and Garrod, S. (2007), 'Do People Use Language Production to Make Predictions during Comprehension?', *Trends in Cognitive Sciences*, 11/3, 105–110, https://doi.org/10.1016/j.tics.2006.12.002.
Google Scholar WorldCat

Pickering, M. J., and Garrod, S. (2013), 'An Integrated Theory of Language Production and Comprehension', *Behavioral and Brain Sciences*, 36/4, 329–347, https://doi.org/10.1017/S0140525X12001495.
Google Scholar WorldCat

Pollard, R., Ellis, J. B., Finan, D., and 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).
Google Scholar WorldCat

Puyjarinet, F., Bégel, V., Geny, C., Driss, V., Cuartero, M.-C., De Cock, V. C., Pinto, S., and 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, Article 874032, https://doi.org/10.3389/fnins.2022.874032.
Google Scholar WorldCat

Rao, S. M., Harrington, D. L., Haaland, K. Y., Bobholz, J. A., Cox, R. W., and Binder, J. R. (1997), 'Distributed Neural Systems Underlying the Timing of Movements', *Journal of Neuroscience*, 17/14, 5528–5535, https://doi.org/10.1523/jneurosci.17-14-05528.1997.
Google Scholar WorldCat

Riley, G. D. (2009), '*Stuttering Severity Instrument for Children and Adults* (London: Pearson).
Google Scholar Google Preview WorldCat COPAC

Salmelin, R., Schnitzler, A., Schmitz, F., and Freund, H.-J. (2000), 'Single Word Reading in Developmental Stutterers and Fluent Speakers', *Brain*, 123/6, 1184–1202, https://doi.org/10.1093/brain/123.6.1184.
Google Scholar WorldCat

Sares, A. G., Deroche, M. L. D., Shiller, D. M., and 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.
Google Scholar WorldCat

Schäfers, K., vom Hofe, J., Mende, C., and Hennen, E. (1995), 'Scatman John: Ich bin nicht davon geheilt, daß es mir unangenehm ist zu stottern', *Planet Interview*, November 1, https://www.planet-interview.de/interviews/scatman-john/33389/.
Google Scholar WorldCat

Silverman, F. H., and Bohlman, P. (1988), 'Flute Stuttering', *Journal of Fluency Disorders*, 13/6, 427–428, https://doi.org/10.1016/0094-730X(88)90010-1.
Google Scholar WorldCat

Silverman, F. H., and Silverman, E.-M. (1971), 'Stutter-Like Behavior in Manual Communication of the Deaf', *Perceptual and Motor Skills*, 33/1, 45–46, https://doi.org/10.2466/pms.1971.33.1.45.
Google Scholar WorldCat

Singer, C. M., Hessling, A., Kelly, E. M., Singer, L., and 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.
Google Scholar WorldCat

Slis, A., Savariaux, C., Perrier, P., and Garnier, M. (2023), 'Rhythmic Tapping Difficulties in Adults Who Stutter: A Deficit in Beat Perception, Motor Execution, or Sensorimotor Integration?', *PloS One*, 18/2, Article e0276691, https://doi.org/10.1371/journal.pone.0276691.
Google Scholar WorldCat

Smith, A. (2010), 'Development of Neural Control of Orofacial Movements for Speech', in W. J. Hardcastle, J. Laver, and F. E. Gibbon, eds, *The Handbook of Phonetic Sciences*, 2nd ed. (Malden, MA; Oxford, UK: John Wiley and Sons), 251–296.
Google Scholar Google Preview WorldCat COPAC

Smith, A., and Weber, C. (2016), 'Childhood Stuttering: Where Are We and Where Are We Going?', *Seminars in Speech and Language*, 37/4, 291–297, https://doi.org/10.1055/s-0036-1587703.
Google Scholar WorldCat

Smits-Bandstra, S., and de Nil, L. F. (2007), 'Sequence Skill Learning in Persons Who Stutter: Implications for Cortico-Striato-Thalamo-Cortical Dysfunction', *Journal of Fluency Disorders*, 32/4, 251–278, https://doi.org/10.1016/j.jfludis.2007.06.001.
Google Scholar WorldCat

Spencer, C., and Weber-Fox, C. (2014), 'Preschool Speech Articulation and Nonword Repetition Abilities May Help Predict Eventual Recovery or Persistence of Stuttering', *Journal of Fluency Disorders*, 41, 32–46, https://doi.org/10.1016/j.jfludis.2014.06.001.
Google Scholar WorldCat

Stager, S. V., Jeffries, K. J., and Braun, A. R. (2003), 'Common Features of Fluency-Evoking Conditions Studied in Stuttering Subjects and Controls: An H215O PET Study', *Journal of Fluency Disorders*, 28/4, 319–336, https://doi.org/10.1016/j.jfludis.2003.08.004.
Google Scholar WorldCat

STAMMA (2022), '*How Many Adults Stammer?*', 11 February, https://stamma.org/news-features/how-many-adults-stammer.
Google Scholar Google Preview WorldCat COPAC

Terband, H., Maassen, B., Guenther, F. H., and Brumberg, J. (2009), 'Computational Neural Modeling of Speech Motor Control in Childhood Apraxia of Speech (CAS)', *Journal of Speech, Language, and Hearing Research*, 52/6, 1595–1609, https://doi.org/10.1044/1092-4388(2009/07-0283).
Google Scholar WorldCat

Thompson-Lake, D. G. Y., Scerri, T. S., Block, S., Turner, S. J., Reilly, S., Kefalianos, E., Bonthrone, A. F., Helbig, I., Bahlo, M., Scheffer, I. E., Hildebrand, M. S., Liégeois, F. J., and Morgan, A. T. (2022), 'Atypical Development of Broca's Area in a Large Family with Inherited Stuttering', *Brain*, 145/3, 1177–1188, https://doi.org/10.1093/brain/awab364.
Google Scholar WorldCat

Tichenor, S. E., and 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.
Google Scholar WorldCat

Toyomura, A., Fujii, T., and Kuriki, S. (2011), 'Effect of External Auditory Pacing on the Neural Activity of Stuttering Speakers', *Neuroimage*, 57/4, 1507–1516, https://doi.org/10.1016/j.neuroimage.2011.05.039.
Google Scholar WorldCat

Toyomura, A., Fujii, T., and Kuriki, S. (2015), 'Effect of an 8-Week Practice of Externally Triggered Speech on Basal Ganglia Activity of Stuttering and Fluent Speakers', *Neuroimage*, 109, 458–468, https://doi.org/10.1016/j.neuroimage.2015.01.024.
Google Scholar WorldCat

Toyomura, A., Fujii, T., and Sowman, P. F. (2021), 'Performance of Bimanual Finger Coordination Tasks in Speakers Who Stutter', *Frontiers in Psychology*, 12, Article 679607, https://doi.org/10.3389/fpsyg.2021.679607.
Google Scholar WorldCat

van de Vorst, R. (2013, September 30), 'Musical stuttering: similar to speech stuttering?: *International Stuttering Awareness Day',* https://isad.live/isad-2013/papers-presented-by-2013/musical-stuttering-similar-to-speech-stuttering/.
WorldCat

van de Vorst, R. (2020), '*Behavioral and Electrophysiological Correlates of Induced (Dys)fluency Conditions in Adults Who Stutter*', PhD dissertation, McGill University, https://escholarship.mcgill.ca/concern/theses/h702qb95h.
Google Scholar Google Preview WorldCat COPAC

van de Vorst, R., and Gracco, V. L. (2017), 'Atypical Non-verbal Sensorimotor Synchronization in Adults Who Stutter May Be Modulated by Auditory Feedback', *Journal of Fluency Disorders*, 53, 14–25, https://doi.org/10.1016/j.jfludis.2017.05.004.
Google Scholar WorldCat

van Riper, C. (1982), *The Nature of Stuttering*, 2nd ed. (Englewood Cliffs, NJ: Prentice-Hall).
Google Scholar Google Preview WorldCat COPAC

van Riper, C., and Emerick, L. (1984), *Speech Correction: Principles and Methods*, 7th ed. (Englewood Cliffs, NJ: Prentice-Hall).

Google Scholar Google Preview WorldCat COPAC

Van Zaalen-op't Hof, Y., Wijnen, F., and De Jonckere, P. H. (2009), 'Differential Diagnostic Characteristics between Cluttering and Stuttering—Part One', *Journal of Fluency Disorders*, 34/3, 137–154, https://doi.org/10.1016/j.jfludis.2009.07.001.
Google Scholar WorldCat

Walsh, B., Mettel, K. M., and Smith, A. (2015), 'Speech Motor Planning and Execution Deficits in Early Childhood Stuttering', *Journal of Neurodevelopmental Disorders*, 7/1, Article 27, https://doi.org/10.1186/s11689-015-9123-8.
Google Scholar WorldCat

Walsh, B., Usler, E., Bostian, A., Mohan, R., Gerwin, K. L., Brown, B., Weber, C., and Smith, A. (2018), 'What Are Predictors for Persistence in Childhood Stuttering?', *Seminars in Speech and Language*, 39/4, 299–312, https://doi.org/10.1055/s-0038-1667159.
Google Scholar WorldCat

Webster, R. (1977), *The Precision Fluency Shaping Program: Speech Reconstruction for Stutterers—Clinician's Program Guide* (Roanoke, VA: Communications Development Corp.).
Google Scholar Google Preview WorldCat COPAC

Wieland, E. A., McAuley, J. D., Dilley, L. C., and 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.
Google Scholar WorldCat

World Health Organization (2019/2021), 'International Classification of Diseases, *Eleventh Revision* (ICD-11)', 'https://icd.who.int/browse11.
WorldCat

Yairi, E., and 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.
Google Scholar WorldCat

Yairi, E., and Ambrose, N. G. (1999), 'Early Childhood Stuttering I', *Journal of Speech, Language, and Hearing Research*, 42/5, 1097–1112, https://doi.org/doi:10.1044/jslhr.4205.1097.
Google Scholar WorldCat

Yairi, E., and Ambrose, N. G. (2004), '*Early Childhood Stuttering for Clinicians by Clinicians* (Austin, TX: Pro-Ed).
Google Scholar Google Preview WorldCat COPAC

Zhu, M., Chen, F., Chen, W., and Zhang, Y. (2025), 'The Impact of Executive Functions and Musicality on Speech Auditory-Motor Synchronization in Adults Who Stutter', *Journal of Speech, Language, and Hearing Research*, 68/1, 54–68, https://doi.org/10.1044/2024_JSLHR-24-00141.
Google Scholar WorldCat