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# The importance of the motor system in the development of music-based forms of auditory rehabilitation

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## Abstract

Hearing abilities decline with age, and one of the most commonly reported hearing issues in older adults is a difficulty understanding speech when there is loud background noise. Understanding speech in noise relies on numerous cognitive processes, including working memory, and is supported by numerous brain regions, including the motor and motor planning systems. Indeed, many working memory processes are supported by motor and premotor cortical regions. Interestingly, lifelong musicians and nonmusicians given music training over the course of weeks or months show an improved ability to understand speech when there is loud background noise. These benefits are associated with enhanced working memory abilities, and enhanced activity in motor and premotor cortical regions. Accordingly, it is likely that music training improves the coupling between the auditory and motor systems and promotes plasticity in these regions and regions that feed into auditory/motor areas. This leads to an enhanced ability to dynamically process incoming acoustic information, and is likely the reason that musicians and those who receive laboratory-based music training are better able to understand speech when there is background noise. Critically, these findings suggest that music-based forms of auditory rehabilitation are possible and should focus on tasks that promote auditory–motor interactions.

KEYWORDS
aging, hearing, motor system, music, rehabilitation, speech-in-noise

## INTRODUCTION

Difficulty understanding speech in background noise is one of the most commonly reported hearing issues for older adults.[1–3] Recent research has shown that musicianship is associated with an enhanced ability to understand speech in noise and that musical training can improve the ability to understand speech in noise.[4,5] While most studies show a musician benefit,[4,5] some studies in younger adults failed to demonstrate a musician advantage.[6–10] Most critically, the research in older adults consistently shows a musician advantage.[11–13] Even older adults who took music lessons during childhood but did not become musicians exhibit speech processing advantages over people who did not have music lessons, and these advantages are related to how much training they received.[14] Interestingly, improved hearing abilities may be related to preservation of cognitive abilities in older adults. Specifically, there is emerging evidence that hearing difficulties are associated, and may be predictive of cognitive decline in older adults.[15] This is consistent with the idea that there are implicit associations between cognitive, sensory, and sensorimotor changes across the lifespan.[16] Overall, it is likely that music training could be used as a foundation to develop auditory rehabilitation programs for older adults that would improve their ability to understand speech when there is loud background noise, and may have cascading effects on other cognitive domains.

  

## IMPORTANCE OF THE MOTOR SYSTEM IN HEARING

A putative music-based auditory rehabilitation program to improve the ability to understand speech in noise would rely on enhancing perception of acoustic information. Perceptual learning often follows a pattern of reverse hierarchy, where higher order brain structures (i.e., frontal lobes) are impacted by the learning first.[17] Plasticity then extends to lower order brain structures, such as primary/secondary sensory regions or subcortical structures that would be more specific to the learned perception.[17] Higher order cortical processing of acoustic information occurs along the dorsal and ventral pathways, and projects to the dorsolateral and ventrolateral prefontral cortex (DLPFC and VLPFC), respectively, in the frontal lobe.[18,19] Functionally, the ventral stream is associated with processing "what" is producing the auditory stream, while the dorsal stream is associated with processing "where" the stream is located or "how" the spectral information of the stream changes over time.[20] For speech, the ventral stream is involved in identifying the speaker, while the dorsal stream is involved in extracting the verbal message from the speaker, whereas in music, the ventral pathway is involved in processing to identify the instrument, while the dorsal stream is involved in processing the melody and how it evolves over time.[20] Critically, the dorsal stream passes through supplementary motor and premotor regions in the frontal lobe, and these regions are activated by speech, music, and nonspeech vocalizations.[21] This idea is consistent with the idea of neural "simulation."[22] In this case, the motor system "simulates" the actions the vocal articulators would make if the listener was to produce the incoming speech.[23]

Involvement of the motor system in simulation of speech perception is well known. Over 30 years ago, Liberman and Mattingly[24] proposed that phonetic information is perceived in a specialized neural module that simulated the intended vocal articulations of the talker. Functional neuroimaging studies have confirmed that brain regions that were traditionally thought to be associated only with speech production are also involved in speech perception. For example, Broca's area, in the left inferior frontal gyrus, is critical for both the production and perception of speech sounds.[25,26] Additionally, regions in the precentral gyrus that extend into the anterior portion of the central sulcus are active during the production and perception of speech sounds.[27] The activations in these regions have been shown to be specific to the sound being perceived. For example, lip regions of the motor strip, which are involved in producing a [p] sound are activated when perceiving a [p] sound, while tongue regions of the motor strip, which are involved in producing a [t] sound, are activated when perceiving a [t] sound.[28]

Interestingly, this speech-motor system becomes increasingly active when processing speech as background noise level increases.[29] Multivoxel pattern analysis using functional magnetic resonance imaging (fMRI) data revealed that specific speech tokens were better discriminated in the ventral premotor regions and in Broca's area when background noise was –6 dB speech-to-noise ratio (SNR) or above.[29] A similar analysis in auditory regions along the superior temporal plane was only reliable when the SNR was much higher at +8 dB SNR (i.e., quieter background noise and easier to understand).[29] These findings provide support for the hypothesis that the motor system is critically involved in the perception of speech when there is loud background noise.

If musicianship is associated with enhanced processing of speech in the motor system, then activity in Broca's area and other premotor regions should be enhanced in musicians compared to nonmusicians when performing a speech-in-noise task. Du and Zatorre[30] revealed that the musician advantage for understanding speech in noise was related to enhanced activity in both Broca's area and in right auditory regions. Moreover, musicians exhibited higher discriminability of speech phonemes in background noise in Broca's area and its right hemisphere homolog, the left and right premotor areas, and in auditory regions along the superior temporal plane.[30] Finally, functional connectivity between auditory and motor regions was found to be enhanced in musicians compared to nonmusicians.[30] Overall, this pattern of results supports the idea that part of the musician advantage for processing speech in noise comes from enhanced activation of the speech-motor system and enhanced connectivity between auditory inputs and the motor system.

Importantly, enhancement to cortical encoding of auditory information in the motor system could propagate to lower order brain regions involved in pitch processing.[17] Support for this proposal comes from research which has shown that cortical motor regions send and receive information directly to and from the inferior colliculus of the auditory midbrain.[31] By definition, any form of instrumental music training requires optimizing motor responses to generate precise sounds (e.g., fingers on piano/guitar, lips/tongue/diaphragm for singing, or horns, etc.). For the information from the motor system to descend the corticofugal pathway and impact auditory neurons in the auditory cortex or brainstem, there would have to be a consistent mapping of specific motor activations to specific acoustic information. In music performance, there is a coupling, but it is not exact. For example, a pianist could play any note on the piano with their index finger. At the same time, the movement of the index finger would have a direct mapping to the loudness of the note, and its "expressive" quality. For speech or singing, the mapping is much more direct. The shape of the vocal tract, particularly the shape and orientation of the tongue, is correlated with the frequency of the first three formants (F1, F2, and F3) in vowel sounds.[32] When speech is presented in background noise, the place of articulation that leads to variability in F2 is the most difficult feature to detect based on acoustic features alone; however, it is one of the easier features to detect based on the movement of a talker's lips.[33] Interestingly, musicians have greater neural differentiation of the F2 consonant-to-vowel transition compared to nonmusicians,[34] and older musicians exhibited a similar advantage compared to older nonmusicians.[35] Importantly, the differences between musicians and nonmusicians were further enhanced when speech material was presented with corresponding videos of lip movements.[36] This pattern of results suggests that the observation of motor movements can further facilitate speech processing in musicians. Over time, this strengthened auditory–motor connection, driven by music training, could give rise to neuroplastic modulations that extend to the level of the auditory cortex or brainstem via the corticofugal pathway.

## MUSICAL TRAINING AND THE MOTOR SYSTEM

Musical training may be one of the most optimal ways to promote auditory–motor plasticity because one of the foundational skills in a musician is a tight coupling between the auditory and motor systems.[37] Even performing a very simple song requires rapid and accurate auditory processing that can be used to rapidly modify upcoming motor movements. In both expert musicians and nonmusicians who have undergone short-term musical training, activity in premotor areas is observed when listening to a melody that the individual knows how to play, suggesting that training leads to an intrinsic connection between perception and production.[38,39] Interestingly, nonmusicians show activation in premotor areas when listening to music, providing evidence that the brain may automatically engage the motor system when processing incoming musical information.[40] It is likely that this connection is because of rhythm or timing. A recent meta-analysis of 42 passive music listening studies that used fMRI revealed that premotor regions, primary motor regions, and the cerebellum were all involved in music listening.[23] One explanation for this is that the motor system is involved in making temporally precise predictions about actions.[23] Supporting this hypothesis are studies that show activations in motor regions when participants attend to temporal features of an incoming auditory stimulus, and that these regions are not active when the same participants attend to different acoustic features in the same stimuli.[41] Not surprisingly, many neuroscientific studies of rhythm reveal activity in motor regions,[37,42–44] and rhythmic musical skills are related to the ability to understand speech in noise.[45] This connection is likely due to the importance of synchronizing to the rhythm/prosody of speech during speech perception. When understanding speech in background noise, an enhanced ability to entrain to the temporal envelope of speech rhythms embedded in noise would allow the listener to better guide their attention to critical acoustic features in the speech signal. Indeed, older adults who are better able to track the temporal envelope of speech in noise are also better able to understand speech in noise.[46] Moreover, a strengthened auditory-motor system could facilitate the suppression of background noise when it contains information that can be modeled by the speech motor system (i.e., by containing speech with a predictable prosody, or through simulation of the vocal articulators). Finally, simulation of the movement of the vocal articulators could aid in prediction of upcoming speech sounds because the movement of the vocal articulators is constrained by their physical structure. Overall, the musician advantage for understanding speech in noise is likely related to enhanced abilities in tracking temporal information through the motor system or enhanced abilities to simulate the putative articulatory or motor gestures used to produce the incoming acoustic information using the motor system.

The motor system plays a critical role in speech perception, particularly when there is loud background noise, and the motor system is improved by musicianship. This leads to the possibility that music-based forms of auditory rehabilitation could improve the ability to understand speech in noisy environments and that this benefit would be due to enhancements to motor regions that are involved in auditory perception. The next section of this paper will review studies that have explored the ability to understand speech in noise in lifelong musicians, or in nonmusicians who were provided musical training.

## MUSICAL TRAINING AND HEARING ABILITIES

There are two broad methodologies that can be used to explore the potential impact of musical training on hearing abilities: cross sectional and longitudinal. Cross-sectional work usually involves comparing a group of people who have received some form of musical training to a group of people who have not received any music training. Longitudinal work usually involves providing some form of musical training to a group of participants and comparing performance before and after training. In many cases, longitudinal studies will also compare to a control group, which in some cases is a "no-contact" group, while in others, there is an active control group that does some other form of learning that is thought to not impact hearing abilities (e.g., visual art lessons, video games, etc.). Cross-sectional research in this area is much easier to conduct compared to longitudinal work, and accordingly, there are many more cross-sectional studies compared to longitudinal studies. Most of the cross-sectional work has already been summarized in both a review[4] and a meta-analysis.[5] Accordingly, the next section will review the main findings from these two articles.

### Comparing younger musicians and nonmusicians

In the past decade, several studies have shown a musician advantage for various speech-in-noise tasks;[4,5] however, some have failed to identify this advantage.[6–10] Coffey *et al.*[4] reviewed research comparing musicians and nonmusicians on the ability to detect an auditory signal embedded in a masker, which included a number of studies that tested the ability to understand speech when there was background noise. Twenty-seven of the 29 papers included in the review reported at least one condition where musicians outperformed nonmusicians or reported that musicians, compared to nonmusicians, exhibited different neurophysiological responses using electroencephalography (EEG) or magnetoencephalography. Despite the vast majority of studies reporting some benefits of musicianship on the ability to detect a signal embedded in a masker, there were many situations where one study reported null effects, while another reported significant effects for a similar task. Two critical findings emerged from this review. First, all studies that examined neurophysiological responses reported differences in brain activity between musicians and nonmusicians when processing words, phonemes, and tones when no background noise was present. Second, most of the studies found a behavioral advantage for musicians compared to nonmusicians when the masking noise was multitalker babble. It is, therefore, likely that musicians have an advantage over nonmusicians for both processing the target speech and suppressing background noise that contains meaningful information (i.e., there is informational masking present). In fact, one of the earliest studies in this domain found a musician advantage over nonmusicians for release from informational masking, while reporting no musician advantage for release from energetic masking.[47] Further support for this proposal comes from more recent studies that both reported a musician advantage for understanding speech, when the background noise was also speech, and a lack of musician advantage when this informational masking was reduced or eliminated.[48,49] Moreover, Yoo and Bidelman[48] reported that the musician advantage was related to working memory abilities and the years of training for each musician.[48] Accordingly, the musician advantage for release from informational masking could be due to an enhanced ability to inhibit the background speech or to successfully divide attention and comprehend both the target speech and the background speech.

More recently, Hennessy *et al.*[5] conducted a meta-analysis on cross-sectional studies that compared musicians and nonmusicians on speech-in-noise tasks. This meta-analysis focused on 31 studies, and found that being a musician was significantly associated with an enhanced ability to understand speech when there is background noise. Importantly, Hennessy *et al.*[5] included many of the studies that failed to find differences between musicians and nonmusicians,[6–10] suggesting that there is a real but small and variable advantage for musicians on speech-in-noise tasks. Furthermore, 18 of the 31 studies in this meta-analysis were also included in the review published by Coffey *et al.*[4] providing meta-analytical evidence for their conclusions. Overall, the picture is now fairly clear that younger musicians are better than younger nonmusicians at understanding speech when there is speech or speech-like background noise.

## Comparing older musicians and nonmusicians

There are fewer studies that compare older musicians and nonmusicians on speech-in-noise tasks, despite the fact that difficulty understanding speech in noisy environments is one of the most commonly reported hearing issues for older adults.[1–3] Two of the first studies that examined hearing abilities in older adult musicians found advantages for older lifelong musicians.[11,13] Parbery-Clark *et al.*[11] compared older (i.e., 45–65 years) musicians and nonmusicians on three speech-in-noise tasks (QuickSIN, HINT, and WIN). They found musician advantages across all three tasks that were related to both auditory working memory and auditory temporal acuity. Zendel and Alain[13] compared musicians and nonmusicians who ranged in age from 18 to 91 years on the QuickSIN test and found slower rates of age-related decline on the QuickSIN in musicians compared to nonmusicians. In this study, the average 70-year-old musician performed as well as the average 50-year-old nonmusician on the QuickSIN test. Zendel and Alain[13] also reported that older musicians were better than older nonmusicians at segregating concurrent sounds based on harmonic structure and detecting a small silent gap. Zhang *et al.*[50] also reported an advantage for older musicians compared to older nonmusicians on a variety of speech-in-noise tasks using Mandarin, suggesting that the effects generalize beyond the English language. Moreover, using a path analysis, they found that the speech-in-noise benefit observed in older musicians was mediated by working memory performance.[50] Accordingly, there is very likely to be a benefit to understanding speech in noise for older musicians that is associated with enhanced working memory abilities and enhanced auditory processing abilities. Although none of these studies explored the underlying neurophysiology, a recent review highlights that working memory abilities are supported by the motor planning system, including Broca's area, the supplementary motor area, premotor regions, cerebellum, and the basal ganglia.[51] Marvel *et al.*[51] suggest that these secondary motor regions are used to generate internal traces that reinforce the contents of working memory and allow it to be manipulated. Accordingly, it is likely that part of the advantage musicians have in understanding speech in noise is due to neuroplasticity in the motor system that benefits both working memory and simulation of incoming acoustic information.

One of the weaknesses of this conclusion is that the advantages observed in older musicians could be associated with pre-existing factors. For example, it is possible that people with enhanced working memory abilities, or a more robust motor system are more likely to become musicians, and that musical training itself offers no protective benefit on the ability to understand speech in noise. Indeed, nonmusicians who perform well on tests of musical perception have enhanced speech and speech-in-noise encoding compared to nonmusicians who perform poorly on tests of musical perception.[52] Most critically, Mankel and Bidelman[52] highlight that formally trained musicians have an additional boost in neurobehavioral functions associated with speech processing, suggesting that enhanced speech-in-noise perception that is typically observed in musicians is due to both inborn characteristics and music training. Longitudinal studies that evaluate the ability to understand speech in noise before and after musical training can help us understand how musical training benefits hearing abilities in people who may not have inborn speech perception advantages.

## Longitudinal music training studies with a focus on understanding speech in noise

One of the most powerful ways to determine if there is a causal relationship between musical training and enhanced abilities to understand speech in noise is through a randomized controlled trial (RCT). Unfortunately, an ideal RCT that explores the putative benefits of musical training on the ability to understand speech in noise in older adults is likely impossible. Musical training often begins early in childhood, and some studies comparing musicians and nonmusicians on auditory, cognitive, and neurophysiological measures have shown that age of training onset is associated with the benefits of musical training.[53,54] For an RCT, this would mean starting the study in early childhood. In order to observe the effects of musical training later in life, these children would have to be tracked throughout life, which would mean the research would have to be conducted by multiple generations of scientists. Moreover, a proper RCT requires a blinded placebo-control group, and ideally, a no-contact control group, which is likely impossible as participants will know if they are getting music lessons or not. Furthermore, this ideal RCT would also require ensuring participants randomized into both control groups are never exposed to music lessons. Clearly, this ideal RCT is impossible given the ethical and time constraints. At the same time, a number of smaller-scale longitudinal studies that explore how hearing abilities change over shorter periods of time (weeks to months to years) have been conducted, and in general, support the idea that at least some of the differences between musicians and nonmusicians in the ability to understand speech in noise are caused by music training.

One of the first studies to explore the impact of music training on the ability to understand speech in noise was done on a group of 7- to 8-year-old children. Slater *et al.*[55] randomly assigned a group of children to either immediately join a community music program or to serve in a delayed control group that would start 1 year after the first group. After 2 years of music lessons, participants improved their ability to understand speech in noise compared to the delayed control group.[55] This study provides causal evidence that the speech-in-noise advantage reported in many studies is at least partially caused by music training, and is not due to in-born differences between people who choose to become musicians and people who do not become musicians.

Given that difficulties understanding speech in noise are common among older adults,[1] there has been growing interest in longitudinal studies that provide music training to older adults. Zendel *et al.*[12] and Fleming *et al.*[56] randomly assigned older adults to receive piano lessons, video game training (placebo control), or no activity (no-contact control) for a period of 6 months and evaluated speech-in-noise performance (word detection in none, quiet, and loud background noise) as well as late positive event-related potential (ERP) components extracted from EEG data before, midway, and after training. Performance in the loudest background noise condition improved only in the group that received music training;[12] that is, 6 months of music lessons improved the ability to understand speech in noise in older adults. In terms of cortical effects, participants in the music group showed an increased positivity over fronto-left electrodes that was related to their increased ability to understand speech in noise.[12] A source analysis of the ERP data,[12] and fMRI data collected in parallel,[56] suggests that these enhancements were related to structures in the speech-motor system, including the left inferior frontal gyrus (Broca's area), bilateral middle frontal gyrus (including the supplementary motor area), the supramarginal gyrus, and the cerebellum.[12,56] Training-related change in these regions was associated with enhanced ability to understand speech across all levels of background noise, supporting the connection between speech understanding and the speech-motor system.[56] Other research has identified these regions as being critical for both speech production and speech perception, providing further support that they are part of the speech-motor system.[57] Additionally, these areas are also part of the motor system that supports working memory.[51] Overall, these results highlight that music training–related improvements to understanding speech in noise arise due to neuroplastic changes in the motor system.[12,56]

In another longitudinal study, Dubinsky *et al.*[58] found that 10 weeks of choir participation improved the ability to understand speech in loud background noise. The improvement in the ability to understand speech in noise was mediated by improvements in pitch discrimination, which was predicted by the strength of the neural encoding of speech stimuli, as assessed by measuring the frequency-following response (FFR).[58] Using the FFR, it has been shown that the subcortical encoding of speech presented in background noise is more robust in musicians compared to nonmusicians.[36,59–63] Although these enhancements were at the subcortical level, it is thought that they were due to top-down control or changes in long-term potentiation, which arose via the corticofugal pathway.[64–66] This idea was based on the reverse hierarchy theory, which states that perceptual learning is a top-down process, and as perceptual learning progresses, the associated neural plasticity will move to lower-level brain structures, if the perceptual learning is challenging.[17]

While Zendel *et al.*[12] and Fleming *et al.*[56] both demonstrated that short-term music training impacted motor regions, Dubinsky *et al.*[58] reported enhancements to the FFR after short-term music training. It is, therefore, possible that music training first impacts the connection between the auditory-motor system at the cortical level, and as music training continues, neurons in subcortical structures are then refined via top-down mechanisms. Existing efferent connections between the motor system in the cortex and subcortical auditory structures provide biological support for this proposal.[31]

Two more recent studies have confirmed a speech-in-noise benefit in older adults as a result of both piano lessons[67] and choir participation.[68] Worschech *et al.*[67] randomly assigned over 150 older adult participants to either receive piano training or to learn about musical culture and measured their ability to understand speech in noise before and after. They reported that both groups showed improvement in the ability to understand speech in noise; however, when the testing was done in only a single ear, the group that received piano lessons showed greater improvement when the speech and noise were presented to the left ear, but not the right.[67] The specificity of the piano lessons effect on the left ear suggests that the improvement observed may be related to right-lateralized frequency discrimination abilities.[67] Indeed, research has shown that older, lifelong musicians have enhanced auditory-evoked responses from right auditory regions.[69] Given the importance of right auditory regions for fine-grained pitch processing,[70] and that Dubinsky *et al.*[58] found enhancements to the FFR, which arises from the brainstem (a lower order structure), these findings are consistent with the reverse hierarchy theory of perceptual learning.

Hennessy *et al.*[68] randomly assigned older adult participants to either a choir singing group or to a passive music listening group. In this study, there was no improvement in the ability to understand speech in noise in either the singing or passive listening groups. Although no behavioral effects were observed, enhancements to the N1 component of the auditory-evoked response were observed in response to both a syllable-in-noise task and an oddball task only in the choir singing group.[68] This result suggests that after participating in a choir, older adults may start to direct increased attentional resources to processing incoming acoustic information, which would be reflected in an enhanced N1 response.[68] In this study, one might expect behavioral benefits to emerge after a longer period enrolled in the choir. Again, this result is consistent with neural plasticity progressing from cognitive and attentive processing to lower levels of processing.

## Longitudinal music training studies with a focus on cognitive abilities

If musical training in older adults improves the ability to understand speech in noise through the motor system, then it is likely that parallel improvements to working memory will also be observed in older adults given music training because of the importance of the motor system in working memory.[51] Degé and Kerkovius[71] provided 15 weeks of singing and drumming lessons to a group of older adults and found that visual and verbal working memory were enhanced in this group compared to a group that received a literature training program, and a no-contact control group. Bugos *et al.*[72] provided individualized piano lessons to a group of older adults and found that after 6 months of lessons, working memory improved on some measures compared to a no-contact control group. Specifically, the group that received music lessons improved on the digit symbols test from the WAIS-III and on the Trail Making B test, but not the digit backwards or letter–number sequencing test from the WAIS-III, nor the Trail Making A test.[72] One particularly interesting finding from this study was that the benefits were maintained 3 months after the end of the music lessons.[72] Seinfeld *et al.*[73] provided 4 months of weekly group piano lessons to a group of older adults and compared their performance to a nonrandom sample that was selected to match the demographics of the participants who volunteered for the piano lessons. This control group was given a variety of leisure activities to choose from, including things like exercise, painting lessons, philosophy lessons, and so on. The group that received music lessons showed improvement on the digit span test from the WAIS-III and on the Trail Making A test, as well as on the word/color Stroop task, compared to the control group.[73] What is interesting is that both Bugos *et al.*[72] and Seinfeld *et al.*[73] found that music lessons improved performance on digit span and trail making tests, both classic assessments of working memory.

More recently, Alain *et al.*[74] provided 3 months of music training using body percussion, voice, and nonpitched instruments as well as some music theory. Participants were randomly assigned to either receive this music training, to receive art lessons, or to serve as a no-contact control. The group that received music lessons improved on a word-color Stroop test compared to both the art training and no-contact control groups. Alain *et al.*[74] also administered other cognitive assessments, including the digit span test, but did not report any significant effects. In addition to these psychometric measures, Alain *et al.*[74] measured brain responses using an auditory oddball paradigm and a visual go/no-go task. In both the art and music groups, the N1 and P2 of the auditory-evoked response was enhanced compared to the no-contact control group. In the visual go/no-go task, participants in the music group exhibited an enhanced P3 response over the right hemisphere and an enhanced P2 response, suggesting that music training improved inhibitory control, which is a critical part of reducing distracting information from working memory.[74] Finally, Guo *et al.*[75] randomly assigned a group of older adults to either receive 4 months of keyboard lessons or to serve as a no-contact control. In this study, the group that received music lessons showed improved verbal working memory. Guo *et al.*[75] also collected fMRI data during the working memory task and found changes in activation during the working memory task in right supplementary motor regions, left precuneus, and the posterior cingulate. These more recent neurophysiological studies highlight that music training enhances brain responses associated with working memory and some of these enhancements arise from motor regions in the cortex.

A final series of longitudinal studies that compared auditory-motor training to auditory-only training in terms of cortical brain plasticity highlights the importance of engaging the motor system in putative music-based forms of auditory rehabilitation. In these studies, younger nonmusicians were randomly assigned to either learn to play a musical sequence on a piano (i.e., auditory-motor condition), or to listen to sequences and to detect errors in their production (i.e., auditory-only condition) over the course of 2 weeks.[76,77] Although these studies were done in younger adults, they highlight the importance of auditory-motor training when exploring plasticity in the auditory system. Each participant in the auditory-only condition was paired with a participant in the auditory-motor condition so that both groups were exposed to the exact same stimuli during the training. The only difference was that the auditory-motor group produced the melodies with specific finger sequences, while the auditory-only group listened to these recorded sequences and detected errors in them.[76,77] After the training sessions concluded, auditory abilities were assessed by using an oddball paradigm, where participants listen to sequences of musical notes with occasional deviants, while their brain activity was monitored using EEG. In Lappe *et al.* (2008),[76] the deviant tone was an out-of-key note in an arpeggio, while in Lappe *et al.* (2011),[77] the deviant tone was 100 ms shorter than the other tones in an arpeggio. In both cases, the response to the deviant evoked a mismatch negativity (MMN), a negative deflection automatically generated in response to a deviant, or unexpected, tone.[78] It should be noted that the wave identified as an MMN by Lappe *et al.* (2008)[76] was likely an early right anterior negativity (ERAN), which is a response to a note or chord that violates musical syntax.[79] Importantly, enhancements to the ERAN are commonly observed in lifelong musicians compared to nonmusicians,[80–83] suggesting that the changes in these short-term training studies parallel enhancements observed in lifelong musicians. Overall, this pattern of results highlights the importance of motor involvement during training in order to instantiate long-term modulations of auditory perception.

## SUMMARY

It is likely that music training improves coupling between the auditory and motor systems, and that this results in improved ability to understand speech in background noise. Interestingly, research examining age-related changes in speech production revealed no significant age effects in motor or premotor regions.[84,85] This is in contradistinction to auditory regions, which show age-related changes in structural morphology, related to hearing acuity,[86] and frontal regions, particularly, prefrontal regions, that show significant decline in both gray and white matter volumes.[87] It is, therefore, possible that musical training and continued musicianship are able to use the motor system as a form of cognitive scaffold because of its relative strength compared to other brain regions in older adults.[88] Indeed, evidence suggests that short-term music training improves the ability to process speech due to functional enhancements in brain regions involved in the speech-motor system.[12,56] This motor system scaffold could develop automatically due to the intrinsic connections between the auditory, sensory, and motor systems, and because the representation of incoming auditory information is enhanced in belt areas around the primary auditory cortex, when it is paired with tactile sensory information.[89,90] This pairing would occur naturally when playing a musical instrument, and provide a more robust representation of the auditory information as it is processed. This enhancement is critical, as developing a motor skill (e.g., playing a musical instrument) requires gathering and processing of sensory information related to the action.[91] Thus, when learning to play a musical instrument, the learner must integrate the auditory information in order to refine the associated motor action in the future. Over time, this leads to a greater connectivity between the auditory and motor systems and may lead to plasticity in motor and premotor cortices and regions that connect the auditory and motor systems. Given that age-related changes in the peripheral auditory system decrease the quality of the incoming acoustic signal, this strengthened pathway might be exploited to help refine this impoverished incoming auditory information. Indeed, integration of multiple modalities can improve the processing of a single sensory modality.[92] In music training, the constant pairing of an auditory input with both a motor command and sensory feedback would increase the cortical representation of the auditory signal. After training, the strengthened auditory-motor system may better process speech information. Given that the motor system is naturally involved in speech perception and with working memory, the enhancements would occur automatically. The result would be that speech processing is enhanced by music training and ongoing musicianship.

One limitation to the main claims made throughout this article is that the musician benefit for understanding speech in noise does not only arise from plasticity in the auditory-motor system. First, it is possible that parts of the plasticity observed in the studies reported above are not related to the motor system at all. That is, there could be plasticity in auditory, frontal, or other brain regions that are not directly involved in the motor system. Accordingly, there may be multiple mechanisms that drive music training–related neuroplasticity. Second, there is now a small body of literature highlighting the importance of inborn characteristics when comparing musicians and nonmusicians. For example, scores on personality tests of both parents and children predict the likelihood that a child will take and continue to take music lessons.[93,94] In nonmusicians, measures of musicality are related to how well the brain encodes speech sounds.[52] Finally, a study of twins revealed that the phenotypic associations between music practice and motor timing could be accounted for by genetics alone.[95] These studies highlight that there are predispositions associated with both musicianship, processing speech, and motor timing. Although there are a number of longitudinal studies demonstrating a benefit of musical training on the ability to understand speech in noise, it is very likely that individual differences play a role in who benefits most from music training.

Overall, it is likely that music training can be used as a form of auditory rehabilitation for older adults. Putative programs should focus on connecting sound to movement in a deliberate way in order to drive changes in brain regions involved in motor planning, which over time could refine auditory-processing abilities, starting in premotor and motor regions, then progressing to primary/secondary auditory regions, and eventually to the level of the brainstem. These changes would improve the ability to understand speech in noisy environments. The impact of these programs could be significant, as age-related decline in hearing is one of the most common health issues in older adults, and difficulty understanding speech in noise is the most commonly reported hearing difficulty in older adults.[1,96]

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## COMPETING INTERESTS

The author declares no competing interests.

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