Dual Training Effects of Bilingualism and Music on Auditory-Motor Integration

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Abstract

Dual Training Effects of Bilingualism and Music on Auditory-Motor Integration

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Musicianship and bilingualism are both demanding sensorimotor processes that require extensive training and expertise to master. Functional changes have been observed in the dorsal pathway comprised of auditory and motor regions of the brain, a network critical for linking sounds to action, a process called auditory-motor integration. Due to this neural overlap, musicianship has been shown to impact aspects of speech processing. The primary goal of our study was to investigate such a "dual training effect" of musicianship and bilingualism. We recruited two groups of bilingual individuals, with one group also being highly trained musicians, controlled on a number of critical demographic factors. We hypothesized that this type of training would result in converging patterns of functional activity at rest within auditory-motor brain networks and impact ability to reproduce non-native language sounds in a more native-like way.

In Study 1, we investigated the impact of being both musician and bilingual on resting-state functional connectivity within the dorsal-auditory motor stream. We observed that musician bilinguals possessed significant decreases in rs-FC between the left IFG pars triangularis and three separate brain clusters comprised of the STG/SMG, left insula, and right insula. We also observed a series of correlations between these reductions in rs-FC and performance on cognitive and musical tasks.

In Study 2, we investigated this dual training impact on ability to listen to and correctly reproduce non-native language sounds. No group differences were found for NNL reproduction

overall. However, we observed a significant correlation between rs-FC reductions observed in Study 1 and these NNL reproduction tasks. When running a series of hierarchical regressions, we observed that musicianship as a grouping variable significantly predicted this performance.

Taken together, our results demonstrate that combined musicianship and bilingualism results in significantly decreased resting-state functional activity between brain areas organized within the dorsal-auditory motor network. Furthermore, we observed that participants with the greatest reductions in rs-FC performed best on tasks assessing spatial organization and working memory, musical rhythm reproduction, and non-native language reproduction. Therefore, we hypothesize that possessing this dual experience may result in a more efficient or streamlined circuit, which may also relate to improved performance on other cognitive tasks, including language tasks.

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I would also like to thank my wife Ashley for her consistent support, not only throughout graduate school, but for motivating me to go back to school in the first place many years ago. She has been alongside me throughout all of my post-secondary education endeavours and milestones and it is doubtful that I could have achieved what I did without her steadfast love and support.

Finally, I would like to dedicate this thesis to our son, William Gunther, who was born in November, 2021, mere weeks after I completed a first draft of this dissertation.

Contribution of Authors

This thesis was part of a larger research project focusing on music and bilingual experience done in collaboration with Dr. Denise Klein at the Montreal Neurological Institute in Montreal, Quebec, Canada. A number of collaborators were involved in this project across multiple roles, including: **Brian Gunther**: Conceptualization, formal analysis, investigation, writing – original and final drafts, reviewing and editing, project administration. **Dr. Lucia Vaquero**: Conceptualization, formal investigation, analysis, project administration. **Paul-Noel Rousseau**: Formal analysis, investigation, project administration. **Diana Vozian**: Formal analysis, investigation. **Dr. Virginia Penhune**: Conceptualization, writing – review and editing, supervision, funding acquisition. **Dr. Denise Klein**: Conceptualization, funding acquisition.

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CHAPTER ONE: GENERAL INTRODUCTION

Human beings have the remarkable ability to acquire expertise across multiple highly complex activities. Playing an instrument is a prime example of a domain of expertise that is a uniquely human phenomenon. Musicality has existed in a ubiquitous fashion across all human cultures throughout history. At its very core, musical expression played a fundamental role in the organization of human societies and may have allowed for the expression of emotions that would facilitate social bonding (Besson et al., 2011). As a songwriter myself, I can attest to the fact that it is sometimes more gratifying to communicate ideas and affect via music rather than simply doing so verbally. The ability to become proficient on a musical instrument – to listen to and produce music in a coherent and harmonious manner - has fascinated auditory cognitive neuroscientists for years. In effect, the musician's brain serves as a practical model of neuroplasticity, as long-term and intensive training on a musical instrument is known to produce both neurological and behavioural changes in human beings (for an in depth review on the neural correlates of music training, see (Zatorre et al., 2007). In order to examine the specific processes involved in the mastering of something like a musical instrument, researchers have investigated the effect of this experience on both the brain and behaviour. However, what occurs when individuals possess expertise across multiple domains, such as with the addition of a second language? As a bilingual individual who is also a musician, this is a longstanding question I have asked myself. Further, what would be the consequence if both of these domains involved a number of shared factors? Would this produce a so-called "additive" or "dual-training" effect? If so, would this impact brain organization and extend to behaviours outside the realm of the original area of expertise?

Learning a second language is a similarly complex auditory-motor task that requires extensive, long-term practice to master. Music and speaking a language parallel one another in terms of being intensive and enriching auditory-motor experiences overall (Jackendoff, 2009; Peretz et al., 2015). Both are used in a number of intriguing ways by human beings in order to communicate, and largely depend on auditory learning to take place in order for them to function as intended (Patel, 2014). In fact, research has demonstrated that playing an instrument and speaking a second language not only have widespread impact on brain organization, but that music itself may affect auditory and motor skills relevant for speech and language (Kraus & Chandrasekaran, 2010; Skoe & Kraus, 2013). This is thought to result from perceptual and cognitive parallels between music and language, and from the overlap of the brain networks involved in both activities. The main purpose of this dissertation was to examine such an impact, delving into the potential "dual-training" effect of being a proficient bilingual as well as a highly trained and skilled musician. Specifically, we sought to directly test the impact of long-term experience and training across two highly-related auditory-motor domains on in-vivo brain connectivity and on non-native language perception and production. In particular, we were interested in possible changes within the dorsal auditory-motor stream, which is organized and comprised of brain areas that are known to be integral in mapping the sounds we hear to the actions we produce (Hickok & Poeppel, 2007).

To do this, we examined two groups of proficient bilinguals with and without music training. These groups completed a battery of language, music and cognitive tasks, as well as structural and resting-state functional connectivity MRI scans. In the first chapter of this thesis, I directly compared diverging resting-state functional connectivity patterns within the dorsal auditory-motor stream between the two groups and examined its relation to musical and cognitive abilities. In the second chapter of this thesis, I used the same two groups to examine whether dual bilingual and music training would modify non-native performance on non-native language perception and production tasks. Studying the possible combined effects of bilingualism and musical training is a challenging endeavour. The current thesis was developed as part of a larger project in which we initially planned to test a large sample of monolingual and bilingual musicians and non-musicians. However, obtaining an adequate sample of monolinguals who spoke with French or English in the Montreal area proved difficult, and subsequent plans and attempts to recruit monolingual participants in Ontario were derailed by the COVID-19 pandemic in March 2020. Thus, the current thesis is only a first step in examining potential dual-training effects of musicianship and bilingualism. By comparing groups of closely matched bilinguals who do or do not have musical training, we can identify how music training combined with bilingualism may modify in-vivo brain connectivity and musical and language-related skills. However, without a monolingual control group, we cannot identify additive effects of the different types of training. Nonetheless, by examining measures of language proficiency and musical training in our analyses, we can begin to explore these questions.

Music as a Complex and Multi-Faceted Sensorimotor Activity

A singer-songwriter is defined as an individual who composes, sings, and performs pieces of music. Well-known singer-songwriters who have honed their craft across multiple decades and have had a lasting impact on my own compositions include artists such as Nick Cave, Mark Kozelek, and Steven Wilson, to name a few. Listening to any of these musicians performing one of their songs beautifully encapsulates how complex and multifaceted a sensori-motor activity playing music truly is. Such a performance involves multiple, simultaneous, and intensely demanding cognitive parameters that must exist in harmony in order for the musical piece to be delivered accurately. What are the cognitive processes and neurological foundation that allow an individual to effectively perform on their respective instruments? Practice is a crucial factor. Playing an instrument is known to recruit a number of primarily auditory and motor areas in the human brain (Herholz & Zatorre, 2012) and long-term musical training can result in experience-dependent plasticity in these brain areas, many of which are part of an intricate network within the human dorsal-auditory motor stream. The dorsal stream is comprised of auditory and motor areas crucial for transforming the sounds we hear to actions we produce, resulting in a phenomenon called auditory-motor integration (Hickok & Poeppel, 2007). This audio-motor integration is in turn essential when playing a musical instrument, and playing an instrument is itself both a demanding and complex sensory-motor activity. Moreover, when a singer-songwriter performs, they need not only learn how to hierarchically time several precise actions, but also have to develop fine motor movements and learn to recognize various subtleties in pitch and sequencing simultaneously. Once mastered, this makes for an impressive display. This process of auditory-motor integration was a primary phenomenon of interest when designing the research experiments discussed within this dissertation. Being a singer-songwriter myself, there was also an inherent interest in examining the neural and cognitive substrates of the activity I am most passionate about.

Through a neuro-cognitive lens, there are myriad factors that come into play when playing a song. Singing and playing an instrument, such as the guitar, requires a specific, sustained type of attention. It necessitates selective attention, requiring the player to intensely focus on various dimensions of sounds and actions. If I am playing an E minor chord, I must focus on the pitch and the collective ensemble of the various individual notes making up the chord structure. Simultaneously, I must ensure I am both in tune and in time. A vital consideration is that, along with the *auditory* features of the chord itself, I must also be attuned to the fine *motor* movements necessary to produce these sounds. If I am finger picking using what is commonly known as "Travis-style picking" (think *Dust in the Wind* by Kansas), then not only am I producing intricate motor movements with my right hand overall and creating the chord shape with my left, but I am independently controlling and moving my thumb, index finger, middle finger, and ring finger in a highly specific and controlled fashion. In fact, this has been observed in violin players, who demonstrate increased cortical representations of left-hand fingers (Elbert et al., 1995). The addition of singing lyrics on top of the music adds yet another level of complexity, reinforcing how this activity is a quintessential example of auditory-motor integration in full, impressive display.

It is no wonder that music has fascinated human beings for millennia and continue to serve as an important model of neuroplasticity to neuroscientists worldwide. The above example demonstrates that playing an instrument requires great precision in its motor action, elicits emotional responses, requires long-term repetition to master, specific sustained levels of attention, and all are reciprocal in maintaining and reinforcing musical skill, eventually relating to transfer. This fits into the OPERA hypothesis (i.e., Overlap, Precision, Emotion, Repetition, Attention - which will be explored in further detail in a subsequent section) proposing that, in order for music to drive neuroplastic and behavioural changes in speech processing, these factors must be present and music must place higher demand on these factors that speech (Patel, 2011). As mentioned, another important consideration is the reciprocal nature of these individual factors. Repetition and practice resulting in finally being able to play a practiced piece of music is a rewarding experience. In this respect, the emotional component relates to the fact that music engages the reward network. In fact, there is a large literature positing that rewarding stimuli are learned with greater ease (see ref and intrinsic vs extrinsic motivation literate). Music is engaging and pleasurable. This positive reinforcement may boost an individual's attention and auditory processing which may motivate this individual to repeat the process. This repetition results in regular practicing and honing precise movements over time, simultaneously fine-tuning sustained attention, and being consistently rewarded which leads to a repeat in the entire cycle. Considering our present results through this lens, over time, long-term musical training has been shown to facilitate certain aspects of speech. This may be due the fact that playing music is an excellent way to train auditory working memory and attention simultaneously.

Language as a Similarly Complex Activity

Along with being a veritable hub for music neuroscience research, Montreal is also one of the most bilingual environments in North America. According to a recent census, it is estimated that an average of 55.1% of individuals speak both English and French fluently, with 21% reporting being proficient in a third language or beyond as well (StatsCan, 2016). As a result, this allowed us the opportunity to investigate the impact of bilingualism on in-vivo brain organization and performance on unfamiliar foreign language tasks. It also allowed us to examine the impact of possessing this type of *dual expertise* and whether an "additive effect" may result from being a trained musician in addition to being bilingual. When compared to learning a musical instrument, learning a new language is an equally challenging, demanding, complex, and dynamic process. A bilingual individual's brain is essentially perceiving and producing sets of sounds that differ phonologically, semantically, and syntactically (Berken et al., 2017). Another fascinating element is that a bilingual individual's lexicon is effectively doubled in size due to their expertise in two distinct languages. For an English-French bilingual, each English word has a French counterpart that exists and is organized within that individual's brain. The brain's ability to navigate between and decipher both of these languages and to produce them is in itself a complex sensory-motor activity, much like playing an instrument, and also requires auditory-motor integration to take place. Both of these overarching areas of expertise are a testament to the human brain's impressive versatility and profound capacity for neuroplasticity. Importantly, these areas of expertise also point towards global similarities between both musical and language-related processes. Due to these well-studied parallels between both the domains of music and language, a natural research question emanating as a result is whether or not there exists cross-domain interactions between both. Due to the overlap in functions between music and language, past studies have examined how music skills can lead to various language-related benefits, which will be covered in more depth later on in this section.

Overlap and Shared Components

Music and language share a number of critical elements and this overlap in brain structures and functions is what is thought to lead to transfer between them. Brain regions implicated in both music and speech are organized within the human auditory-motor pathway (Hickok & Poeppel, 2007). This framework proposes a dual-route model of speech processing, positing that the auditory-motor network itself is divided into two streams – both a ventral and a dorsal pathway. The ventral pathway (the *what* pathway) is thought to be important for translation of *sound to meaning,* helping us make sense of what we hear by transforming auditory signals to the subjective meaning attached to this signal. This is important for proper comprehension of heard speech and involves areas within the anterior temporal lobe and inferior frontal lobe (IFG). Conversely, the dorsal pathway (the *where or how* stream) is said to be integral for translation of *sound to action*, allowing us to map the sounds we hear to the actions we produce. This results in a process called auditory-motor integration, which is vital for the domains of both music and speech, and will be the primary pathway of interest discussed in this thesis. Specifically, the dorsal stream is critical for the mapping of incoming acoustic signals to the frontal lobe and articulatory networks comprised of an organization of brain regions in the articulatory and sensorimotor networks comprised of the posterior auditory regions, inferior parietal lobule, premotor cortex, the inferior frontal gyrus and the insula. In this model, the superior temporal gyrus (STG) acts as an intermediary important for analysis of spectro-temporal information. A prime example of the STG's critical role in auditory-motor integration comes from studies examining lesions in this area, where damage to the left dorsal STG results in a speech deficit referred to as *conduction aphasia,* which results in frequent phonemic errors when producing speech, albeit adequate comprehension remains (i.e., in this instance the ventral stream, the *what* stream, is unaffected) (Damasio & Damasio, 1980). Another important consideration is that the IFG is thought to play a role within the articulatory network of the human brain that also includes the premotor cortex and the insula. There are also hemispheric considerations when examining the dorsal pathway's role in music and speech. In a previous study using the same data set, it was found that participants who had learned their second language earlier in life demonstrated leftward increased volume of the long segment of the arcuate fasciculus whereas participants who began playing an instrument earliest in childhood exhibited rightward increased volume (Vaquero et al., 2020). This asymmetry as a result of long-term, sustained involvement in either a second language (leftwards) or music (rightwards) has also been demonstrated in previous research studies (Hämäläinen et al., 2007; Halwani et al., 2012).

Playing an instrument and speaking a language both incorporate acoustic elements such as pitch, timing, and timber to relay pieces of information (Kraus et al., 2009). Moreover, both music and speech place significant emphasis on elements of cognition such as demands on memory and attention, as well as transforming sounds to meaning (Patel, 2011; Hickok & Poeppel, 2007). Both are ubiquitous in human cultures around the world. Through an evolutionary lens, the seemingly innate drive to produce musical sounds may have arisen due to human beings' natural disposition towards speech production and communication. Conversely, it is entirely possible that the opposite is true – that music may have preceded language throughout human evolution and that language itself may build upon our natural tendency towards music (Peretz et al., 2015). Through a cognitive lens specifically however, the learning and processing of both music and language involves a number of functions that parallel those implicated in other cognitive domains. Briefly, the processing of both music and language necessitate considerable memory capacities, the development of specific cognitive schemas, finely-tuned vocal and hand control, the ability to imitate and integrate observed actions into one's own repertoire, the ability to create and store new information, and the ability to engage in joined and cooperative action (Jackendoff, 2009).

Given these similarities, a recent area of examination (and a central focus of this dissertation) explores *cross-domain plasticity*, especially from music to language. Specifically, cross-domain plasticity between music and language would involve assessing how intensive music experience, as well as the long-term neural processing involved herein, may impact the neural processing of speech and language. In order to properly explore cross-domain plasticity between two intensive auditory-motor training experiences such as music and language, a number of pertinent questions arise, including – can music actually drive neural plasticity in neural networks involved in auditory processing that is also relevant for language? Further, and importantly, *why* would this occur? The study of potential transfer effects from music to language in the auditory cognitive neurosciences is largely motivated by the prominent neural overlap between brain structures that are engaged when playing music or speaking a language. Importantly, the existence of this neural overlap was a primary driving factor motivating our own research questions found within this thesis and is a central element of the OPERA hypothesis.

In the OPERA hypothesis, Patel (2014) explores why these enhancements might occur, and suggests that, in order for music to drive neuroplasticity and to produce possible enhancements in language, certain conditions must be met. These conditions are: O = overlap, P = precision, E = emotion, R = repetition, and A = Attention. The first factor parallels one of the primary considerations of the present thesis - that is, the neural overlap in brain regions that are critical for processing the acoustic features in both music and language, which will be reviewed in more depth in a subsequent section of this thesis. Patel (2014) continues to argue that, for plasticity to occur, another four specific conditions must be met. Subsequent to the neural overlap involved, Patel (2014) also suggests that precision, emotion, repetition, and attention must be present, and that the combination of these elements may lead to cross-domain plasticity from music to language. In terms of precision, Patel proposes that music effectively trains the auditory system to enable precise auditory processing and discrimination. Further, music elicits a strong emotional response, and these responses contribute to learning. Finally, it is also important that the musical activity engaging this network be performed in a repetitive manner and that they result in focused attention when engaging such a network. Given the satisfaction of these factors, Patel argues that music has the potential to affect language-based networks as a result. On a related note, there are a number of recent studies which show not only cross-domain *neural plasticity* when considering music to language, but specific enhancements to speech and language *ability* as a result of musical experience.

A number of studies have emerged examining this prominent overlap including parallel activation of both functionally and structurally connected brain areas that are organized within the dorsal auditory-motor stream. These include the well-studied impact of both music and language on the IFG, with a particular emphasis on Broca's area in the left hemisphere. Research has demonstrated that the inferior frontal gyrus (IFG) has been shown to be implicated in various aspects of music and speech, such as processing patterns of pitch within songs, processing prosody, and coding spoken words (Merrill et al., 2012). In the same study, the bilateral STG was also found to be implicated in a significant overlap between the processing of words and pitch patterns in both songs and speech. Importantly, recent analyses examining connected brain networks have revealed that auditory and motor networks form a highly interconnected 'hub' that are shared by the processing of both music and language (van den Heuvel & Sporns, 2013). As a result, this overarching analogous brain activation within these networks is interpreted as evidence that music and language share similar underlying neural circuitry (Peretz et al., 2015). A main reason for this observed coactivation may be due to the fact that both music and language provide an intense auditory-motor training experience across an extended period of time, and both require expertise to master.

Transfer Effects from Music to Language

When consistent experience in a particular domain impacts the processing of elements in a second domain, this is referred to as a specific *transfer effect*. Relating this idea of transfer back to Patel's (2014) OPERA hypothesis, music has been shown to impact aspects of speech processing. For example, there is a growing body of literature positing that musicianship may lead to enhanced sensitivity to speech and language sounds (Besson et al., 2011). A few notable examples include findings that, when compared with non-musicians, musicians may possess globally enhanced acoustic processing, which in turn may result in enhancements to pitch tracking accuracy (Bidelman et al., 2011), enhanced sensitivity to lexical tone and segmental variations in language

(Marie et al., 2011), and increased sensitivity to deviations in metrical structure and word pronunciation (Magne et al., 2007). These results are interpreted as demonstrating that experience-dependent plasticity can arise as a result of intensive music training which may cause plasticity within the same neural networks also important for speech. However, a natural extension of this question arises – what specific *behavioural effects* can musical training have on general *performance* when it comes to speech and language? How exactly does proficiency on a musical instrument translate to aspects of speech perception and production, above and beyond the plastic neural changes observed? Researchers have examined this precise question by investigating the impact of musical training, on auditory learning in general and the development of particular speech and language skills (for an excellent review on auditory learning in musicians, see Strait & Kraus, 2014). For example, evidence from such studies indicate a wide array of diverse transfer skills from music to language, including enhanced ability to discern speech in noisy environments and greater selective auditory attention (Parbery-Clark et al., 2009, 2013); (Zendel & Alain, 2009; Strait & Kraus, 2011) better reading ability (Banai & Ahissar, 2013, (Moreno et al., 2009; Strait et al., 2010), increased linguistic abilities (Moreno et al., 2009), and overall enhanced speech perception (Parbery-Clark et al., 2012). A particularly well-researched area of study demonstrates that people with music training are better able to discern speech in noisy environments compared to individuals without music training (Parbery-Clark et al., 2009; (Strait et al., 2012). This may be due to the fact that musical training may strengthen working memory and auditory attention overall (Patel, 2014; Strait & Kraus, 2011; Besson et al., 2011). A recent meta-analysis also proposes that phonological awareness and reading fluency are enhanced in individuals that possess expertise on an instrument (Gordon et al., 2015). Researchers have argued that proficiency on an instrument may increase one's sensitivity or ability to fine tune various acoustic features that are inherent to both music and speech processing (Strait & Kraus, 2011; Besson et al., 2011).

Studies Involving Children

Developmental studies with children are a prime opportunity to examine music-related enhancements and benefits across early development. Studies show a positive transfer from music education to phonological awareness, including rhyming, but transfer to elements related to reading skills necessitate further study (Gordon, 2015). An important consideration is that brain plasticity and changes in brain mechanisms in general as a result of musical training in childhood are thought to support cognitive processes associated with music and language, which include enhanced auditory skills overall (Gordon et al., 2015). A parallel can be drawn from this proposal to the OPERA hypothesis as proposed by Patel (2014), where neural overlap between both activities is associated with vital processes such as precision, emotional elicitation, and greater attentional capacities.

Transfer from Bilingualism to Music

Although there is a relatively extensive literature exploring the potential benefits of musicianship on aspects of speech processing, the study of possible transfer from bilingualism to music processing is quite limited. Even though there exist research studies having demonstrated that bilingualism may impact cognition in various ways, there is little research examining the consequences of speaking a second language on music processing and production per se. However, bilingualism itself has been shown to improve cognitive function in multiple ways, with a particular emphasis on executive and cognitive control. This often manifests in enhanced performance on experimental tasks measuring non-linguistic interference, conflict processing and resolution, selective attention, and the ability to deal with competing information, such as the Simon task (Bialystok et al., 2004), the Stroop task (Hernández et al., 2010), the Attention Network Test (ANT) task (Costa et al., 2008), and the Flanker task (Costa et al., 2009). Increased processing ability on these tasks is thought to be indicative of enhanced executive and cognitive control, with bilinguals often demonstrating better performance when compared to their monolingual counterparts. There is also a rich field of bilingualism research assessing the impact of speaking two languages on factors relating to aging, such as dementia and cognitive control. Overall, it is well-understood that bilingualism itself may act as a protective factor and significantly contribute to cognitive reserve (for a review, see Calvo et al., 2016).

Functional and Structural Findings

The positive transfer effects observed from music to language are likely related to the well-studied overlap in brain regions comprising the auditory-motor network. Evidence from both structural and functional neuroimaging studies have shown that musicians show experience-dependent plasticity in brain regions that are part of this dorsal stream. Briefly, as this thesis is primarily focused on functional considerations, previous studies have shown that musicians exhibit greater grey matter volume in auditory cortex (Bermudez & Zatorre, 2005), the inferior parietal lobule (Foster & Zatorre, 2010); the motor cortex (Elbert et al., 1995), and the corpus callosum (Schlaug et al., 1995). Functionally, studies examining both trained and untrained musicians have demonstrated that the dorsal premotor cortex (dPMC) is activated when these people listen to or are engaged in playing music. For example, it has been shown that the dPMC is engaged not only when people are actively playing an instrument, but also when they are listening to music or mentally rehearsing a performance (Bangert et al., 2006). Studies have also shown that activation of the dPMC is also of particular importance when musicians learn to play new melodies (Brown et al., 2015). Resting-state functional MRI (RS-fMRI) is a method of examining correlated activity across brain regions. Brain regions whose activity is highly correlated are thought to be engaged in functionally-specific networks, and the correlations across regions are influenced by factors such as training, experience, or disease state (Lewis et al., 2009). Recently, researchers have begun using this technique in order to extend the research into music and bilingualism's impact on brain plasticity, namely, the in-vivo brain organization resulting from extensive practice and training in these complex sensorimotor activities. Preliminary evidence suggests that musicianship may result in differing (i.e., increases or decreases) levels of rs-FC when compared to non-musicians. For example, it has been found that, when compared to non-musicians, musicians exhibit increases in rs-FC patterns between the right auditory cortex and right ventral premotor cortex (Palomar-García et al., 2017), between the left AC and the cerebellum (Luo et al., 2012), between between the left AC and the left premotor area (Fauvel et al., 2014). Similarly, recent studies have also examined rs-FC alterations in bilinguals when compared to monolinguals, including simultaneous bilinguals exhibiting increased rs-FC between the left and right IFG as well as between the IFG and other language control areas such as the dorsolateral prefrontal cortex, inferior parietal lobule, and cerebellum (Berken et al., 2016). Generally, these studies have observed increases in patterns of functional connectivity at rest, with only one study, to the best of our knowledge, observing that musicians may actually exhibit decreases in rs-FC when compared to non-musicians (Tanaka & Kirino, 2016). These rs-FC studies will be examined in more detail in chapter 2 which details study 1.

The involvement of the inferior frontal gyrus, and specifically the left IFG including Broca's area, has been well studied when examining its critical shared involvement in both music and language comparisons. For example, it has been suggested that connectivity between the left IFG and the right auditory cortex is essential for development of music abilities (Peretz, 2013). Despite brain areas being complex and involved in different processing networks (Peretz et al., 2015), its division in both pars opercularis and triangularis are thought to relate distinctly to aspects of speech, including recognizing of voice tones for the former (Schremm et al., 2018) and translation of second language back to the native language for the latter (Elmer, 2016). Due to the wide-spread neuronal implications of the IFG, a primary question for the present study was to consider the IFG as part of a specific auditory-motor network hub such as the dorsal-auditory motor stream, and to investigate if it plays an integral role in translating sounds heard into motor actions (such as playing an instrument or speech).

Current Study Goals and Hypotheses

The overlap in processes important for playing a musical instrument and speaking a second language has been well studied. There is a growing body of literature suggesting that musicianship may affect and possibly improve certain facets of second language learning. However, there exists a current gap in the broader literature examining the impact of being both a trained musician as well as a proficient bilingual on in vivo patterns of brain connectivity, particularly within the dorsal-auditory motor stream, and whether this 'dual-training' impact could enhance certain aspects of unfamiliar language perception and production. In order to explore this proposed dual-training effect of musicianship and bilingualism, we recruited two groups of proficient bilinguals, with one group also consisting of highly-trained and proficient musicians on their respective instruments. As music and language both recruit similar brain areas organized within a specific network (i.e., the dorsal-auditory motor stream), our first research question was to explore the impact of these two forms of long-term and intensive training on brain connectivity at rest (rs-FC). Due to the IFG's importance in both music and speech and considering that this region itself is a critical part of the dorsal auditory-motor stream, we selected seed regions in this auditory dorsal pathway including, the pars triangularis and opercularis portions of the IFG, STG, SMG, and premotor cortex. We hypothesized that the addition of musicianship on top of bilingualism would result in diverging patterns of brain connectivity at rest for individuals with this dual training, within the dorsal-auditory network. Furthermore, due to suggestive evidence that musicianship itself may confer benefits when it comes to aspects of language processing, we explored this proposed dual-training effect on participants' ability to perceive and correctly re-produce non-native language sounds. Specifically, we hypothesized that combined musicianship and bilingualism would result in two effects in the musician bilingual group: increased ability to discern the subtle Hindi dental retroflex contrast in an experimental task, and increased ability to listen to and most accurately (i.e., more native-like) reproduce words and sentences in Hindi and Farsi. Due to our participants being recruited in a diverse and multi-cultural city like Montreal, we abided by a strict recruitment protocol and controlled for potential differences between the groups by matching our participants on a number of key variables including age, sex, years of education, as well as on language and music variables to ensure comparable L2 experience and music experience. These matching variables will be discussed in subsequent chapters.

CHAPTER TWO: STUDY 1

Resting-state functional connectivity differences as a result of a dual training effect of musicianship over bilingualism?

Abstract

Music and bilingualism are both demanding sensorimotor processes that require extensive and consistent training to master. Engagement in these complex cognitive activities is known to result in structural and functional changes in the brain. Functional changes have been observed in a network or pathway comprised of auditory and motor regions in the brain that allow humans to map the association between sounds to the movements necessary for their production. This auditory-motor integration is of particular importance for both music and speech. Due to the overlap between music and speech and their shared recruitment of similar pathways, we were interested in examining the impact of possessing both forms of expertise on spontaneous brain connectivity, particularly within this dorsal auditory network. Using a rs-FC analysis, we compared two groups of bilingual individuals, with one group also being highly trained and proficient musicians, controlled on a number of critical demographic, musical, and language variables. We observed that musician bilinguals exhibited significantly decreased patterns of functional connectivity at rest between the left IFG pars triangularis and three separate clusters comprised of the aSTG/SMG, and bilateral insula. We also found that these reductions in rs-FC were associated with increased performance on cognitive and musical tasks. These findings suggest that musicianship in addition to bilingualism may result in these two comparably complex activities simultaneously exercising this overlapping network over time, possibly leading to more efficient or streamlined resting brain connectivity that might be important for correct processing of both.

Introduction

Playing an instrument and learning a second language are both demanding and complex sensory-motor processes that require extensive practice to master. Consistent, long-term engagement in these activities has been shown to produce structural and functional changes in similar areas of the human brain, principally in the auditory dorsal stream (Zatorre, 2017; Klein et al., 2014). The dorsal stream is a network connecting posterior auditory with frontal motor and language regions. This network is thought to play a critical role in mapping sounds we hear to actions we produce, in a process called auditory-motor integration (Hickok & Poeppel, 2007). Auditory-motor integration is thought to be crucial in the learning and production of music and speech; and music training itself has been shown to enhance speech processing (Rauschecker & Scott, 2009); Patel, 2014). Evidence from functional neuroimaging studies has demonstrated that musicians and bilinguals both show experience-dependent plasticity in brain regions that are part of and engage the dorsal auditory motor pathway which includes primary auditory and motor cortices, sensorimotor integration areas, and frontal language regions (Costa & Sebastián-Gallés, 2014; Herholz & Zatorre, 2012; Hickok & Poeppel, 2007; Rauschecker & Scott, 2009; Zatorre et al., 2007). Given these parallels between the functional domains of music and language, and the neuro-anatomical overlap of regions reported to be involved in these processes (see (Patel, 2014) OPERA hypothesis for a summary), the goals of the current study were to investigate whether there exists an additive effect of musicianship over and above bilingualism, and if this effect would produce functional connectivity changes in the dorsal stream of bilingual musicians compared to bilingual non-musicians. In order to investigate these proposed changes, we used resting-state functional connectivity (rs-fc) as a measure of in vivo brain organization differences in bilinguals with or without musical training. Groups were matched on age, sex, years of second-language exposure (L2), number of languages fluently spoken, and L2 verbal fluency We also explored the relationship between these changes in functional connectivity and performance on a number of cognitive variables including measures assessing executive function (Simon task), spatial reasoning (Matrix reasoning), and short-term memory (Letter number sequencing).

Language-Related Areas Affected by Bilingualism

Investigation of the differences in brain activity between bilinguals and monolinguals has demonstrated that bilinguals exhibit structural and functional changes in language-related brain areas (for review see, (Costa & Sebastián-Gallés, 2014). For example, bilinguals showed greater BOLD activity during picture naming tasks and reading aloud in the dorsal precentral gyrus, inferior frontal gyrus (IFG) pars triangularis and opercularis, superior temporal gyrus, and planum temporale (Jones et al., 2012). Bilinguals also exhibited greater activity in the left inferior frontal cortex (specifically, BA 45) during comprehension tasks (Kovelman et al., 2008). Structural studies have found increased cortical thickness in the inferior frontal gyrus (IFG) (Klein et al., 2014) as well as increased grey matter in the left inferior parietal cortex (Mechelli et al., 2004). Furthermore, other studies examining white matter (WM) plasticity in bilinguals have demonstrated that bilinguals possess increased WM tracts in language processing and monitoring networks, suggesting the development of more specialized sub-networks to help process two languages (García-Pentón et al., 2014). Specifically, it was found that bilinguals possessed significantly increased connection between frontal and parietal/temporal regions in the left hemisphere including the IFG pars triangularis (IFG PT), superior temporal gyrus (STG), and the insula, among others.

Resting-state functional connectivity is a fairly recent imaging technique that postulates that the brain exhibits spontaneous, in vivo connectivity during wakeful rest even in the absence of task performance. It has been demonstrated that patterns of blood-oxygen level dependent (BOLD) time series are organized in a similar way and mimic those known to be involved when performing a complex sensorimotor task, such as playing an instrument (van den Heuvel & Hulshoff Pol, 2010). Recently, there has been a growing interest in examining the effects of extensive musicianship and bilingualism on these functional connectivity changes *at rest* in the human brain. When comparing bilinguals to monolinguals using rs-fMRI, it has been shown that bilinguals exhibit enhanced intrinsic functional connectivity in the frontoparietal control network and default mode network (Grady et al., 2015). When comparing simultaneous (i.e., having learned two languages from birth) to sequential (i.e., learning a second language later on in life) bilinguals, Berken et al. (2016) found that simultaneous bilinguals exhibited enhanced in vivo brain connectivity between the left and right IFG, a brain area known to be organized in the dorsal-auditory stream. Finally, there is also some evidence that earlier acquisition of a second language may lead to *decreases* in spontaneous brain activity between the default mode network and task-positive attention network, and may impact cognitive control (Kousaie et al., 2017). Taken together, there is a robust literature positing that bilingualism results in significant functional and structural changes in the human brain, particularly in areas relating to the dorsal-auditory-motor stream, that may be affected by such factors as age of acquisition (AOA) and proficiency (Berken et al., 2016; Vaquero et al., 2020). Recent observations may also point to potential functional reductions in these networks, although evidence is limited. Given these changes, we were primarily interested in examining what the impact of additional musical expertise would have particularly on functional organizing of such networks at rest.

Structural and Functional Changes in Trained Musicians

There is a growing body of evidence showing that musicians exhibit changes in resting-state functional connectivity (rs-FC) when compared to non-musicians (Luo et al., 2012); Fauvel et al., 2014; Palomar-García et al., 2017). Similarly, a "neural signature" for bilinguals has previously been proposed, with increases in brain activity appearing primarily in language-related areas in the left-hemisphere when comparing bilinguals to monolinguals (for a review, see Costa & Sebastián-Gallés, 2014)). As for research investigating resting-state functional connectivity changes in bilingual brains specifically, there has been a particular focus as of late on investigating plastic changes as a function of age of start of a second language (Berken et al., 2016; Kousaie et al., 2017). Compared to learning a second language, playing an instrument places similar demands on auditory-motor integration and other cognitive processes. These widespread similarities have been proposed to result in overlap between both domains (for a review, see Patel (2014). Briefly, this overlap is proposed to exist across brain structure and function as well as in terms of cognitive function. For the former, overlap exists in auditory and subcortical networks vital for proper processing of acoustic features, such as pitch. For the latter, the particular cognitive functions that overlap for both activities relate to auditory working memory and auditory attention. In order to properly play an instrument, a musician must simultaneously link the sound emanating from their instrument with the specific movements that are necessary to elicit those sounds. Evidence from functional and structural neuroimaging studies have demonstrated that musicians show experience-dependent plasticity in brain areas that are part of the dorsal stream which partially overlap with those observed in bilinguals. For instance, musicians have been shown to possess enhanced cortical representation within somatosensory/motor systems related to the left-hand fingers of string players (Elbert et al., 1995). Even in the absence of direct performance, there is a growing body of evidence demonstrating that music training can result in enhanced functional connectivity patterns between auditory and motor systems. Notably, Bangert et al. (2006) compared such functional connectivity patterns in pianists and non-musicians while they were either passively listening to piano melodies or playing keys on an fMRI-compatible keyboard while inside a scanner. During both tasks, the musician group displayed greater functional connectivity in areas important for auditory-sensorimotor integration, including the dorsolateral and inferior frontal cortex, the STG, supramarginal gyrus, and supplementary motor, and premotor areas. Not only are these brain regions activated while actively performing a task, but motor regions in the brain (including the PMC, supplementary motor area, and cerebellum) have been shown to be similarly recruited while simply listening to or imaging playing music in the absence of task (Chen et al., 2008; Lotze et al., 2003). In a testing paradigm involving non-musicians learning short piano pieces and subsequently listening to their newly acquired piece without movement while undergoing fMRI scanning, Lahav et al. (2007) observed activation in key areas of the dorsal auditory stream, including Broca's area, the premotor region, and the inferior parietal region. Taken together, researchers have demonstrated different patterns of structural and functional connectivity in musicians while performing, listening to, and even imaging playing music.

In addition to changes in brain structure and the pattern of activated brain regions during specific tasks, there is mounting evidence suggesting that musicians may also exhibit differing patterns of *intrinsic* functional connectivity compared to non-musicians. Intrinsic connectivity is measured from resting-state fMRI. For example, Palomar-García et al. (2017) recently examined in vivo differences in both auditory and motor regions while comparing trained musicians and non-musicians. Using a seed-based resting-state functional connectivity analysis (rs-FC), they demonstrated that musicians exhibited greater intrahemispheric rs-FC between the right auditory cortex (AC) and the right ventral pre-motor cortex (vPMC), with connectivity being stronger in musicians who had more years of training. They also showed that musicians possessed significantly reduced intrinsic functional connectivity between the motor regions important for controlling both hands. In a similar rs-FC study, Luo et al. (2012) examined whether musicians would exhibit a higher level of in vivo functional connectivity in motor and multi-sensory systems when compared to non-musicians. Using an ROI-based rs-FC analysis, they found that musicians possessed significantly increased rs-FC among both motor and multi-sensory cortices when compared to their non-musician counterparts. Specifically, their selected ROIs consisted of the right primary motor cortex, left primary auditory cortex, left primary somatosensory cortex, and the left V2 area. While using four distinct clusters having exhibited significant grey matter volume increases (in a prior associated study) as seed regions for rs-FC analysis, Fauvel et al., 2014) compared in vivo functional connectivity differences between trained musicians and non-musicians. They observed that musicians possessed increased rs-FC changes between these clusters and a number of brain regions known to be important for semantic memory, language, and sensory and motor information. Namely, they found that the right IFG displayed greater intrinsic activity at rest with the claustrum. Conversely, researchers have also examined the opposite. In a recent series of studies from Japan, Tanaka and Kirino (2016) demonstrated that, when compared to non-musicians, trained musicians exhibited decreased in vivo connectivity within the dorsal striatum. In summary, despite this being a more novel and rapidly developing avenue of analysis, there appears to be mounting evidence that trained musicians may exhibit differing levels of intrinsic functional connectivity between auditory and motor areas of the brain, many of which play a pivotal role and are key regions in the dorsal auditory stream.

Dorsal Auditory Pathway and Potential Transfer from Music to Language

The auditory-motor interactions integral to both playing music and learning a second language rely on well-established auditory circuits that travel along both dorsal and ventral routes (Hickok & Poeppel, 2007; Rauschecker & Scott, 2009). It is the dorsal pathway that is thought to be particularly relevant in linking sounds we hear to motor commands. Both music and language recruit a number of brain regions that are organized in the auditory dorsal stream including the inferior frontal, parietal, and premotor regions, and the STG (Hickok & Poeppel, 2007; 2015). The expanded OPERA hypothesis developed by Patel (2014) is based on the overlap between the cognitive function and brain regions engaged in both music and language training. Due to both of these activities involving intensive auditory-motor training, The OPERA hypothesis proposes why a link or overlap may exist between these two domains. According to this hypothesis, active involvement with a musical instrument, and not simply an exposure to, is paramount. This key factor along with a number of other attributes are what might result in this transfer to the language domain. Overall, engagement with music must be active, requires sustained periods of attention, the motor process of the instrument involves precise, repetitive action, and the experience with music is emotionally engaging. Lastly, the overlap in brain structures important for music and language, and critical for auditory-motor integration to occur, are part of the same dorsal auditory network. Research has posited that neural overlap in music and language include highly connected (anatomically and functionally) networks or 'hubs' that may facilitate integration of signals within auditory-motor and cognitive domains, both integral to music and speech processing (van den Heuvel & Sporns, 2013). If these attributes are met, music training can result in plastic changes in speech-processing networks. Further, when considering the neuroanatomical overlap in networks crucial for processing the acoustic features of both music and language, playing music increases the demand on these networks and impacts cognitive processing in a similar way to speech. According to Patel (2014), if these conditions are satisfied, the consequence is increased neural plasticity in this overall shared network, which may result in increased precision when it comes to processing aspects of speech. Relating this back to our current study, a primary goal was to examine the impact of possessing both expertise with music and a second language on the perception and production of foreign-language speech sounds.

Resting-State fMRI and Study Goals

While previous studies have demonstrated differences in individual regions, using resting state fMRI will allow us to examine changes in the entire network. As mentioned, resting-state fMRI is a method of examining correlated activity across brain regions. Brain regions whose activity is highly correlated are thought to be engaged in functionally-specific networks, and the correlations across regions are influenced by factors such as training, experience, or disease state (Lewis et al., 2009). Specifically, we chose to utilize this approach to explore which brain networks might show differing patterns of correlated activity at rest in musicians who happen to also be bilingual when compared to bilinguals who are not musicians. Given the parallels between the functional domains of music and language, and considering the neuro-anatomical overlap of regions reported to be involved in these two demanding auditory-motor experiences, we investigated whether a proposed additive effect of musicianship, over and above bilingualism, would result in differing levels of auditory-motor integration and whether it would elicit plastic changes on similar brain networks when comparing bilinguals with musical training to those who do not have musical training. Specifically, we tested interactions in the dorsal stream and other language-related areas such as the IFG pars triangularis and opercularis, STG, SMG, and premotor cortex. In order to test our hypothesis, we compared musician bilinguals and bilingual non-musicians on a number of behavioural tasks and also using a seed-based resting-state fMRI approach

Method

Participants

We recruited 62 bilingual participants who were divided into two groups: bilingual musicians who had greater than 10 years of musical training and were currently practicing their instrument (n = 31; 15 male/16 female) and bilingual non-musicians who had less than 3 years of musical training and had not played in the last 5 years (n = 31; 12 male/19 female). All participants spoke either English or French as their second language (L2) and the large majority (84%) had English or French as their first language (L1). Other reported first languages included: 4 Mandarin, 2 Cantonese, 1 Dutch, 1 Korean, and 1 Teochew. The bilingual musician and non-musician groups were matched on age, sex, years of second-language exposure (L2), number of languages fluently spoken, English verbal fluency, and French verbal fluency (see Table 1 for language, music and demographic characteristics). Participants were recruited from the Department of Music at Concordia and McGill Universities, and from the general Montreal community. All were self-identified right-handers and had no known history of auditory, neurological or psychiatric disorder. We also ensured participants did not report any experience with Hindi, Farsi, or any other language with similar sounds. Participants gave written informed consent. The research protocol was approved by the Concordia University Human Research Ethics Committee and by the Research Ethics Board of the Montreal Neurological Institute (MNI) of McGill University and was carried out in agreement with the principles of the Declaration of Helsinki.

Music and Language Questionnaires

All participants completed the Musical Experience Questionnaire (MEQ) developed in our laboratory (Bailey & Penhune, 2010). This questionnaire was used to categorize participants into musicians and non-musicians. We extracted musical background variables to quantify experience in the musician group: age-of-start of music training, years of musical experience (total years involved in training and practicing music), years of formal training (total years enrolled in music lessons), and hours of current practice per week. All participants also completed an in-depth language acquisition questionnaire (Marian, Blumenfield, & Kaushanskaya, 2007) that included age-of-start, years of experience and number of languages spoken.

Language Proficiency

Verbal fluency, both phonemic and semantic, was tested for all participants in English and in French, if that was their second language. For the English task, participants were asked to name as many words as they could think of beginning with the letter “A” and pertaining to the category of ‘animals,’ whereas the French task consisted of the letter “L” and the category ‘fruits.’ The participants were recorded, and scores were subsequently calculated by combining the total number of correct utterances. Participants were also asked to subjectively rate themselves on the number of languages they fluently spoke (scale of 1 to 7). In order for a language to be considered “fluent,” the self-rated score had to exceed or be equal to 5.

Music Tasks

Rhythm synchronization task. Participants were asked to listen to and tap in time with six musical rhythms that varied in metrical complexity (Chen et al., 2008). On each trial participants heard a single rhythm twice: the first time they were instructed to listen, and the second time they were instructed to listen and tap in synchrony with their right hand using the computer mouse. There were two blocks of 36 trials in which each rhythm was presented six times in a counterbalanced fashion. Performance was measured using two dependent variables: The percent of correct taps (PC) and the inter-tap (ITI) interval deviation (J. Bailey & Penhune, 2012).

Melody Discrimination Task. Participants were asked to listen to two brief melodic sequences and distinguish if they were the same or different, across two levels of difficulty comprised of simple and transposed melodies (Foster & Zatorre, 2010). All participants completed a total of 30 blocks for either condition and the order of the tasks was counter-balanced with randomized trials within each block. The participants' performance was measured via a composite score comprised of correct responses on both simple and transposed melodies, collapsed into an overall percent correct score. A similar procedure was employed for the control (syllable discrimination) condition. Both the Melody and Rhythm tasks were programmed in the Presentation software (Neurobehavioural Systems, http://www.neurobs.com/) and presented to the participants using a laptop computer, headphones, and a computer mouse that the participants used to respond.

Cognitive tasks

Matrix Reasoning and Letter Number Sequencing tasks. Participants were tested on the Matrix Reasoning (MR) the Letter Number Sequencing (LNS) tasks from the Weschler Adult Intelligence Scale (WAIS-IV; Weschler, 2008). The MR task provides a measure of non-verbal global cognitive function and the LNS task assesses auditory working memory. All scores were converted to age-normed scaled scores for the subsequent analyses.

Simon task. Participants were tested on the Simon task in order to assess executive function and cognitive control (Bialystok et al., 2008; Kousaie et al., 2014). The task was implemented using the E-Prime 2.0.10.353 software (Psychology Software Tools, Inc [E-Prime 2.0] (2013). Retried from http://www.pstnet.com). The Simon task is divided into four distinct experimental conditions, including: (i) control, (ii) reverse, (iii) conflict congruent, and (iv) conflict incongruent. Participants were exposed to the 4 conditions 4 times each and the task was divided into two blocks, with each condition being presented twice in each block for a total of 48 trials altogether, in a fixed order. The specific measure focused on and included in our analyses was the “Simon interference suppression,” which assessed the participants’ ability to suppress interfering spatial information, calculated as an increase in response time for the conflict compared to the control condition (Kousaie et al., 2014).

Image Acquisition

MRI protocol. MRI scanning took place at the Brain Imaging Centre of the Montreal Neurological Institute on a Seimens 3T TrioTim scanner (32-channel head coil). Participants underwent an 8 min 12 sec resting state scan. During this scan they were instructed to lie still, clear their minds and fixate on a cross on the screen. Resting scan images were obtained in 38 3.5-mm-thick transverse slices, covering the entire brain (TR, 2260 ms; TE, 30ms; matrix size, 64 x 64; FOV, 224mm; flip angle 90°). For all subjects, high-resolution T_1-weighted structural images (used as an anatomical reference) were also obtained from a 3D magnetization prepared rapid gradient echo sequence (slice thickness = 1mm, TR = 2300 ms; TE = 2.98 ms, matrix size

= 256 x 256, FoV = 256 mm, flip angle = 9°, interleaved excitation). They also underwent diffusion-weighted scans to assess white-matter integrity.

Data Analysis

Resting-state fMRI data first underwent preprocessing in SPM8 (Wellcome Department of Imaging Neuroscience, London, UK) using standardized spatial preprocessing steps. The images acquired were slice-time corrected, realigned and resliced, normalized in MNI space, and smoothed with a 6mm kernel. A seed-driven approach using the CONN software (Whitfield-Gabrieli & Nieto-Castanon, 2012) was used in order to perform resting-state functional connectivity analyses. The left and right IFG pars triangularis (BA 45) and opercularis (BA 44), premotor cortex, anterior and posterior superior temporal gyri (aSTG; pSTG, and the supramarginal gyrus (SMG) were selected as ROI as defined by the Harvard-Oxford atlas, based on brain regions having demonstrated differing levels of connectivity for musicians and bilinguals in previous research studies (Lahav et al., 2007; Fauvel et al., 2014; Berken et al., 2016). Further, the selected ROI also represent brain regions known to be organized in the dorsal-auditory stream and important for auditory-motor integration.

Functional connectivity analyses were performed using the CONN toolbox. In individual analysis, we examined differing patterns of resting-state functional connectivity between groups using a seed-voxel approach which estimates temporal correlations between the blood oxygen level-dependent (BOLD) signal from our a priori ROI (seeds) and BOLD signal at every brain voxel. Pearson's correlation coefficients were calculated between the time course of the seeded regions and the time courses of all other voxels, which provided a seed-to-voxel connectivity matrix. Positive and negative correlation coefficients defined positive and negative functional connectivity, respectively (Whitfield-Gabrieli & Nieto-Castanon, 2012). The correlation coefficients were then converted to normally distributed scores using Fisher's transform, which were subsequently used in the population-level analysis. The connectivity matrix with converted scores was compared between the musician bilingual and bilingual non-musician groups. The height-threshold of $p < 0.001$, uncorrected, was applied to individual voxels to define clusters. The extracted clusters were thresholded at $p < 0.05$ with the false discovery rate (FDR) correction to report the results. All reported results were significant at the cluster level of FDR correction and all reported clusters survived an FDR threshold of p < .05 and an uncorrected voxel-level threshold of p < .05, two-sided.

Results

***Matching variables for musician and bilingual groups*.**

Bilingual musicians and non-musicians were matched for sex, age, years of education, age of acquisition of L2, years of L2 exposure, number of languages fluently spoken, self-rated L2 fluency, and English and French verbal fluency (See Table 1). We did not observe any significant differences between the two groups on any of these variables, except for the musical experience variables where musicians had significantly more experience than non-musicians.

Musical tasks

Rhythm Synchronization Task. One-way ANOVA for both percent correct (PC) and ITI deviation revealed a significant main effect of group (PC: $F(1, 59) = 19.84$, $p = .0001$; ITI: $F(1, 59) = 41.91$, $p = .0001$), such that musician bilinguals outperformed bilingual non-musicians (Table 3).

Melody Discrimination Task. One-way ANOVA for the composite melody score revealed a significant main effect of group, such that musician bilinguals outperformed bilingual non-musicians in their ability to correctly distinguish between two different melodies across both testing conditions ($F(1, 59) = 139.44$, $p = .0001$; Table 3). One-way ANOVA for the control (syllable) task did not reveal a significant difference between groups on ability to distinguish between two sequences of syllables ($F(1, 59) = 3.72$, $p = .059$).

Cognitive tasks

Scores on both MR and LNS were in the normal range for both groups. One-way ANOVA for both tests showed that musician bilinguals performed better than bilingual non-musicians (Table 3). Musician bilinguals also performed better on the *interference suppression* measure of the Simon Task (Table 3).

Seed-Based rs-FC Analysis

To assess possible differences between groups in rs-FC in the auditory dorsal stream network we conducted a set of seed-to-voxel analyses examining. Specifically, we compared rs-FC between five seed regions and the rest of the brain: the bilateral IFG pars triangularis and opercularis (L + R BA44 and 45), PMC, aSTG and pSTG, and SMG (see table 2 for coordinates). Only the left IFG pars triangularis (L B45) ROI showed significant differences between groups such that bilingual musicians exhibited decreased resting-state functional connectivity with three clusters in the brain: right aSMG/STG ($F(1, 60) = 24.25$, $p = .0001$), left insular cortex ($F(1, 60) = 19.71$, $p = .0001$), and right insular cortex ($F(1, 60) = 25.85$, $p = .0001$) (Figure 4).

Correlation between cognitive task performance and rs-FC. Across all participants, we observed a significant negative correlation between rs-FC of L B45 – SMG and MR ($r = -.478$, $p = .001$ and LNS ($r(61) = -.294$, $p = .021$), such that higher scores on MR and LNS resulted in significantly decreased connectivity at rest between these regions (see Figures 6 and 7). A similar finding was observed between rs-FC of L B45 – L insula and MR ($r(61) = -.490$, $p = .000$) and LNS ($r(61) = -.339$, $p = .007$), whereas higher scores on MR and LNS resulted in significantly decreased connectivity at rest between these regions. Lastly, we observed a significant negative correlation between rs-FC of L B45 – R insula and MR ($r(61) = -.437$, $p = .0001$) and LNS ($r(61) = -.255$, $p = .047$), whereas higher scores on MR and LNS resulted in significantly decreased connectivity at rest between these regions. The same correlations within musician and non-musician groups were not significant, suggesting that group differences in rs-fc may be producing these effects. Within the musician bilingual group specifically, we observed a significant negative correlation between rs-FC of L B45 – R insula and Simon interference suppression score ($r = -.417$, $p = .020$) whereas better performance on the interference suppression score resulted in significantly decreased connectivity at rest between these regions.

Hierarchical regression analysis. In order to examine the contributions of and clarify which variables predicted resting-state functional connectivity observed, and to investigate the existence of a potential group effect of musicianship, a series of hierarchical regression analyses were conducted. We conducted three separate hierarchical regression analyses: 1) L IFG pars triangularis (pt) to SMG cluster, 2) L IFG pt to L Insula, and 3) L IFG pt to R Insula, respectively. In the first step of each regression analysis, Matrix Reasoning and Letter Number Sequencing scores were entered as model 1; in the second step, musicianship (as a group variable) was added as model 2.

Examining musicianship as a predictor

We conducted three hierarchical regression analyses (Cohen, Cohen, West, & Aiken, 1983) to examine the contributions musicianship, MR and LNS on observed rs-FC reductions. MR and LNS were added at step 1 of each model in order to first control for the potential impact of cognitive task performance on rs-FC, and our predictor of interest, musicianship, was added at step 2.

For all clusters, in step 1 MR and LNS accounted for a significant portion of the variance. However, when musicianship was added in step 2, it accounted for a significant additional portion of the variance (range 9-15%), demonstrating that musical training is a unique incremental predictor of rs-FC above cognitive task performance. All three hierarchical regression models can be found in Table 4.

Discussion

In the current study, we investigated the combined effect of bilingualism and music training on resting-state functional connectivity in the brain, examining regions within the dorsal auditory-motor stream known to be important for auditory motor integration. In order to examine these proposed differences in spontaneous brain connectivity, we recruited two groups of bilinguals, one of non-musicians and the other of trained musicians, who were matched on key demographic variables including age, sex, years of second-language exposure, number of languages fluently spoken, and L2 verbal fluency. Across both groups, we observed that musician bilinguals showed negative correlations between activity in the left IFG pars triangularis and three separate clusters comprised of the aSMG/STG, and bilateral insula. We also observed that musician bilinguals scored higher on cognitive tasks assessing general IQ

(MR), auditory working memory (LNS) and executive control (Simon interference score). When investigating the relationship between cognitive task performance and in vivo brain connectivity across all participants, we observed a significant negative correlation between MR and LNS performance and all three rs-FC findings. In other words, the participants whose scaled scores were highest on both the MR and LNS tasks also exhibited the greatest reduction in spontaneous activity between left IFG and STG/SMG and bilateral insula. For musicians only, Simon interference scores were related to reduced rs connectivity between IFG and right insula. Finally, hierarchical regression analyses showed that MR scores and musicianship predicted reductions in rs-FC between IFG and these brain clusters.

Taken together, our findings demonstrate that a dual training experience of musicianship and bilingualism appears to modulate in vivo brain connectivity in auditory dorsal stream regions known to be involved in playing music, speaking a second language, and which are important for overall auditory-motor integration. Music training also appears to enhance aspects of cognitive function and auditory working memory. These findings could suggest a dual effect of long-term musical training alongside the mastering of a second language. Consistent engagement in both of these complex sensorimotor activities may effectively modify correlated activity at rest in brain pathways important for auditory-motor integration, creating a more selective and/or efficient network. This simultaneous exercise is what we believe might lead to greater selectivity or efficiency within this network in individuals that possess long-term experience in these domains. As music and speech make use of shared neural networks, and music training is thought to impact speech (Patel, 2011), we propose that dual training on both can result in a more fine-tuned and efficient network.

Role of IFG in music and language

In the present study, we observed that bilingual musicians exhibited significantly decreased rs-FC between the L IFG pt and clusters comprised of the aSTG/SMG, and bilateral insula. Musicianship and bilingualism are both complex sensorimotor activities that require extensive practice to master. It has been well documented that there is an anatomical overlap in the auditory dorsal stream brain regions recruited by both activities, including the IFG (Hickok & Poeppel, 2015). The left IFG itself has long been established as playing a critical role in language. However, with the advent of more advanced neuroimaging techniques, our understanding of the IFG's function now also extends beyond the borders of language processing, and there is mounting evidence that this brain area is also implicated in other cognitive domains including working memory and, importantly, music. The role of Broca's area in the processing of both music and language has been well researched (Fadiga et al., 2009; (Gernsbacher & Kaschak, 2003; Patel, 2003; (Maess et al., 2001). Studies using fMRI have demonstrated that the IFG becomes activated when one processes both aspects of musical structure (Cheung et al., 2018; Koelsch et al., 2002, 2005; Levitin & Menon, 2003) as well as elements of sentence structure (Just et al., 1996). Further, syntactic organization can be viewed as representing a shared element between music and language, as both activities rely on the organization of various elements in order to form overarching structures. The left IFG particularly has been shown to be quite important for this syntactic organization in both music and language (Fadiga et al., 2009).

Established circuit/network that includes the IFG

The IFG is a key node in the dorsal auditory-motor pathway which includes articulatory and sensorimotor areas including the premotor, anterior insula, and parietal temporal areas (Hickok & Poeppel, 2007). Listening to speech activates the STG, whose role within this pathway has been shown to relate to sound processing and recognizing speech perception. In studies investigating the functional impact of hearing irregular musical chords, it has been shown that listening to such anomalies activated the IFG, STG, SMG, and insula (Koelsch et al., 2005). When considering the circuit or network formed by these structures, the authors posited that these brain areas may form a circuit that may play a role in a number of cognitive elements when it comes to processing musical sounds. It was also proposed that this network may play a role in processing musical syntax – or the "grammar" of music – auditory working memory, and possibly in the emotions elicited by music. Studies have also demonstrated that listening to music taps into this circuit (Janata et al., 2002). Taken together, there is mounting evidence that a neural network or circuit is activated when an individual processes sounds including music and speech. Based on our observed results, we propose that the development of proficiency in both domains exercise these established neural circuits and may render them functionally more selective or efficient over time.

Previous rs-FC findings in musicians and bilinguals

Previous studies have observed differences in resting-state functional connectivity between musicians and non-musicians, particularly in the auditory dorsal stream. However, the majority of these findings have demonstrated increases in rs-FC in musicians. For example, Luo et al. (2012) observed that musicians exhibited a wide array of increased rs-FC in both motor and multi-sensory cortices, including the insula. The authors proposed that long-term musical training may produce a functional consolidation effect, enhancing the integration between these brain areas. Another recent study also observed increased rs connectivity between the insula and wide-scale brain networks involved in salience detection, executive control, and affective processing networks (Zamorano et al., 2017). In general, the insula is thought to play an important role in integrating high-order cognitive control, sensorimotor integration, and emotion processing in music. Among its many known functions, the insula has been known to be implicated in various facets of musicianship and music processing, such as tempo processing (Thaut et al., 2014). Overall, the insula has been shown to represent a 'hub,' thought to contribute to coordinating large-scale networks in the brain, with a particular emphasis on the integration of incoming sensory information as well as executive functions (Cauda et al., 2011).

However, we specifically observed a significant *reduction* in spontaneous brain activity between the L IFG pt the insula and the aSTG. Observing any connectivity between the L IFG pt and the aSTG is not surprising, as both are organized as a network in the dorsal auditory stream and play an integral role in audio-motor interactions (Hickok & Poeppel, 2007). Further, the superior temporal brain areas are known to be of particular importance for mapping actions we hear to sounds we produce (Hickok & Poeppel, 2007; Paraskevopoulos et al., 2012). Studies investigating the role of the STG in musicianship have posited that this region effectively becomes increasingly specialized in order to correctly process music perception, an example of which would be processing patterns of pitch (Zatorre, 1998). In experimental paradigms, listening to pieces of music has been shown to activate the right STG and increased STG activity has also been shown to relate to increased ability to identify scrambled pieces of music in musicians (Matsui et al., 2013). Relating these findings back to the network or circuit that houses these individual regions, it is possible that possessing expertise in two similarly intensive and complex auditory-cognitive activities such as playing music and speaking a second language may have effectively exercised this network over time and led to a more efficient or selective network at rest, in order to meet the constant demand of consistent performance on both of these activities. One other study, to the best of our knowledge, has reported reductions in rs-FC for musicians between the putamen and the FO and ACC. This was also interpreted as potentially signifying that musicianship results in more selective convergence between the putamen and other cortical areas and that musical training may affect the selectivity of the corticostriatal network in general (Tanaka & Kirino, 2016). However, an important point still remains that the participant contrast in this study was also musicians vs non-musicians whereas our participants possessed two levels of expertise.

Cognitive Task Performance

The musician bilingual group performed significantly better on tasks measuring working memory and global cognitive function and on the interference suppression measure of the Simon task. The latter finding on the Simon task has also been observed when comparing bilinguals who have been speaking both languages since birth compared to those who learned their second language after age 6 (Kousaie et al., 2017). Previous studies investigating intelligence and executive functions in musicians have demonstrated that musicians exhibited higher performance on tasks similar to the ones we used in our study (Criscuolo et al., 2019). Namely, it has been shown that musicians possessed increased global cognitive functions, increased working memory and attention, and better conflict resolution when compared to non-musicians, by exhibiting higher performance on the WAIS-III, the Wechsler Memory Scale III, and the Stroop Test (Criscuolo et al., 2019). Overall, given that music training heavily relies on executive functions, these results are not surprising. Although these task increases as a function of musical training have been well researched, a more compelling result in our present study were the correlations observed between task performance and rs-FC decreases within the previously described neural circuits. In the current study, why would musician bilinguals perform better on these cognitive tasks? Overall, long-term engagement in musical training heavily taps into executive functions in general. Playing an instrument itself can be thought of as a complex and intensive multisensory auditory-cognitive activity, one that requires high-order perceptual processing and fine-tuned auditory-motor integration (Münte et al., 2002). Across our entire sample, we observed a series of correlations between global cognitive ability and rs-FC decreases. These correlational analyses demonstrated that a better performance on cognitive tasks resulted in the greatest reduction in rs-FC observed between the seed region and the 3 clusters. Further, hierarchical regression analyses demonstrated that musicianship as a grouping variable accounted for a significant amount of individual variance over and above MR and LNS scores. Therefore, musicianship itself appears to contribute independently to these reductions in rs networks. We propose that this specific finding represents an additional piece of evidence to support our primary hypothesis of greater functional efficiency as a result of musicianship and bilingualism simultaneously exercising this network over time.

Expertise and rs-FC

A number of studies have investigated the impact of developing expertise at a particular skill on brain organization, particularly functional connectivity modulations. Broadly speaking, alterations in functional connectivity in the human brain have been observed as a result of expertise gathered across a large domain of intensive activities, including dancing (ballroom dancing) (Lu et al., 2018), physical activity and sports (badminton, runners) (Di et al., 2012), video games (first person shooters, action video games) (Benady-Chorney et al., 2020), cognitive domains (such as math and chess) (Shim et al., 2021; Duan et al., 2014), and across multiple vocational activities such as sommeliers, architects, and perfumers (Jeon & Friederici, 2017). In a recent review paper, Chang (2014) summarized the extent of plastic brain changes as a result of *expertise* across multiple domains, including music. Overall, it has been well documented that music itself can produce functional changes in brain activation, with a common observing of generally enlarged network connections and focused functional activation, particularly in the motor areas (Chang, 2014). A common finding across all of this literature is a general *increase* in functional activity as a result of expertise. There are, however, several salient examples of studies showing decreased rs-functional connectivity in relation to expertise. For example, a study investigating brain changes at rest between expert ballroom dancers compared to healthy controls, observed a widescale reduction in resting-state functional connectivity between their IFG seed region and a number of temporal and parietal regions (Lu et al., 2018). In this study, the authors posited that these alterations in functional connectivity may be a reflection of the demands of long-term dance expertise, including the need for increased action perception, attentional control, and adjusting fine-tuned movements. If we relate this back to our findings, musicianship and bilingualism also require similar demands, and place significant emphasis on overlapping neural networks that may be exercised over time, potentially resulting in more efficient connectivity within these circuits in order to provide individuals with the necessary auditory-motor elements important for proper processing and performance of both tasks.

Another recent study examined math experts and found that they exhibited significantly *decreased* rs-FC when compared to non-experts, particularly in brain networks involved in high-level cognitive function, such as the left IFG (Jeon & Friederici, 2017). This reduction in in vivo functional connectivity was interpreted as a representing a higher level of "neural efficiency," with a smaller or more confined level of activity for those with a higher level of mathematical expertise. The authors posited that consistent and long-term practice leading to expertise effectively attenuates the dependency on controlled attentional processes, resulting in the cognitive processing of mathematics becoming more automatic and requiring decreased effort and procedural steps, compared to non-experts which exhibited a larger, more broad activation. The idea of extensive practice leading to decreased and more confined activation is nicely summarized in a meta-analysis compiled by Chein and Schneider (2005). In this review, the authors discuss that the research findings consistently point towards a decreased pattern of regional activity as a result of extensive practice.

Overall, studies investigating converging patterns of rs-FC in individuals possessing expertise in a particular domain tend to gravitate towards having observed increases in FC generally. However, an important consideration is that these studies investigated simple, singular contrasts of expertise (i.e., musicians vs non-musicians, early-trained vs late-trained musicians, bilinguals vs monolinguals, etc). An important point is our multi-layered contrast, such that our participants that demonstrated the greatest reductions in rs-FC within auditory-motor networks possessed experience in *two* complex and intensive auditory-cognitive domains that also happen to converge in terms of their structurally and functionally connected network overlap vital for their accurate processing and performance. We believe that simultaneous exercising of associated brain circuits/networks is the primary reason we may have found reductions in rs-FC patterns rather than increases, contrary to previous research. We propose that, due to the anatomical overlap in brain regions known to be key in music and language, and considering this through the lens of a potential dual-training perspective, our findings suggest that consistent engagement in both these activities, in a simultaneous fashion, sufficiently exercises this circuit and may result in a more efficient or modified auditory-motor network, resulting in greater selectivity in order to maximize performance over time. This proposal may relate to the logic of Patel's OPERA hypothesis (Patel, 2014), in which specific factors must be met in order for music to benefit elements of speech processing, with a particular emphasis on the neural overlap and the activity placing sufficient demand on this overlapping network. These findings should be investigated in future studies while considering this proposed dual-training hypothesis as well as recruiting a group of solely monolingual participants in order to observe a potential additive effect across monolingual, bilingual, and bilingual musician groups.

Conclusions and future directions

The primary goal of the current project was to add to our understanding of the extent to which music and language are processed by domain-general auditory and motor processes and/or by distinct neural auditory and speech production mechanisms. Our results demonstrated that a simultaneous dual-training effect of musicianship and bilingualism resulted in decreased patterns of in-vivo brain connectivity in the dorsal-auditory network and provide support for the ongoing hypothesis of "neural efficiency" or "network selectivity" as a result of extensive expertise and training. Musicians and bilinguals can be thought of as experts that have mastered the ability to map the sounds they hear to the actions they produce on their respective instruments. Both of these abilities rely on the the dorsal stream, and both activities entail activation and recruitment of key brain areas known to be organized in this pathway. It is possible that the high demand that two congruent auditory and sensori-motor activities (music and bilingualism) place on this network results in intensive, long-term exercising of this overlapping circuit, resulting in a more efficient or selective network to aid individuals process these two highly intensive domains. Another critical factor is the overlapping functions of both music and language and how they relate to the proposed neural overlap. Over time, playing an instrument and speaking a second language tap into similar functions critical for the elicitation of both, including playing very high demand on auditory working memory and attentional resources. Tying this back to the OPERA hypothesis, while considering both shared network and processes, this may support Patel's

(2014) proposal that intensive and simultaneous music and bilingualism may result in cross-domain impacts and modify the dorsal auditory motor circuit. To date, our study appears to be the first to suggest an overall "dual-training" effect of musicianship and bilingualism. Importantly, it is difficult to examine whether an "additive" effect of music over bilingualism is present in the absence of a monolingual control group. Therefore, future studies should consider examining such a group in order to clarify musicianship's contribution.

Table 1

Demographic and Matching Variables of the Bilingual Non-Musicians (Bil NM) and Bilingual Musicians (Bil Mus)

	Mean age	Sex	Yrs edu	AOA mus train	Yrs mus	AOA L2	Yrs L2 exp	No. lang fluently spoken	Self-rated L2 fluency	Verbal fluency	Sim. bilingual	Seq. bilingual
Bil NM	25.03 (4.25)	12m 19f	14.06 (2.83)	11.33 (2.72)	1.25 (1.43)	5.84 (5.01)	19.19 (6.21)	2.00 (0.00)	5.98 (0.88)	25.37	9	22
Bil Mus	23.07 (4.63)	15m 16f	14.03 (3.08)	7.19 (2.39)	15.74 (4.26)	4.54 (4.32)	18.67 (4.81)	2.13 (0.57)	5.48 (1.52)	29.29	11	20
Sign.	n.s.		n.s.	P<.001	P<.001	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Table 2

Seeds and their coordinates in MNI space

Seed	Cluster location	x	y	z
L IFG pt	Left IFG 45	-50	28	9
R IFG pt	Right IFG 45	52	28	8
L IFG op	Left IFG 44	-51	15	15
R IFG op	Right IFG 44	52	15	16
PMC	Premotor cortex	26	-10	55
aSTG	Anterior division STG	-52	31	9
pSTG	Posterior division STG	53	31	9
SMG	SMG	62	-35	32

Table 3

Cognitive and Musical Variables in Bilingual Non-Musicians (Bil NM) and Bilingual Musicians (Bil Mus); (N = 62)

	MR	LNS	Avg melody	Rhythm % corr	Rhythm ITI avg	Simon interference suppression
Bil NM	9.97 (2.82)	11.03 (3.16)	61.83 (9.57)	0.73 (.074)	0.33 (.042)	91.44 (38.84)

Bil Mus	13.26 (2.42)	13.94 (3.43)	85.19 (4.76)	0.81 (.062)	0.25 (.058)	71.96 (17.99)
Sign.	P<.001	P<.001	P<.001	P<.001	P<.001	P<.015

Table 4

Hierarchical regression models. Summary of Hierarchical Regression Analysis for Variables Predicting musicianship decreases in rs-FC between L IFG and aSTG/SMG

	B	SE B	***β***	*t*	*p*
Step 1					
Constant	.331	.084		3.930	.000
MR	-.023	.007	-.427	-3.478	.001
LNS	-.006	.006	-.137	-1.114	.270
Step 2					
Constant	.219	.084		2.620	.011
Musicianship	-.145	.042	-.448	-3.478	.001

Summary of Hierarchical Regression Analysis for Variables Predicting musicianship decreases in rs-FC between L IFG and L Insula

	B	SE B	***β***	*t*	*p*
Step 1					
Constant	.422	.081		5.230	.000
MR	-.022	.006	-.422	-3.495	.001
LNS	-.008	.005	-.184	-1.521	.134
Step 2					
Constant	.329	.082		4.006	.000
Musicianship	-.120	.041	-.380	-2.928	.005

Summary of Hierarchical Regression Analysis for Variables Predicting musicianship decreases in rs-FC between L IFG and R Insula

	B	SE B	***β***	*t*	*p*
Step 1					
Constant	.418	.094		4.450	.000
MR	-.023	.007	-.396	-3.319	.003
LNS	-.005	.006	-.109	-.862	.392
Step 2					
Constant	.288	.092		3.118	.003
Musicianship	-.168	.046	-.478	-3.642	.001

Figure 3. Correlations between the Matrix Reasoning (MR) task and the rs-FC decrease between IFG pars triangularis (LB45) and 3 separate brain clusters (L_insula, R_insula, SMG)

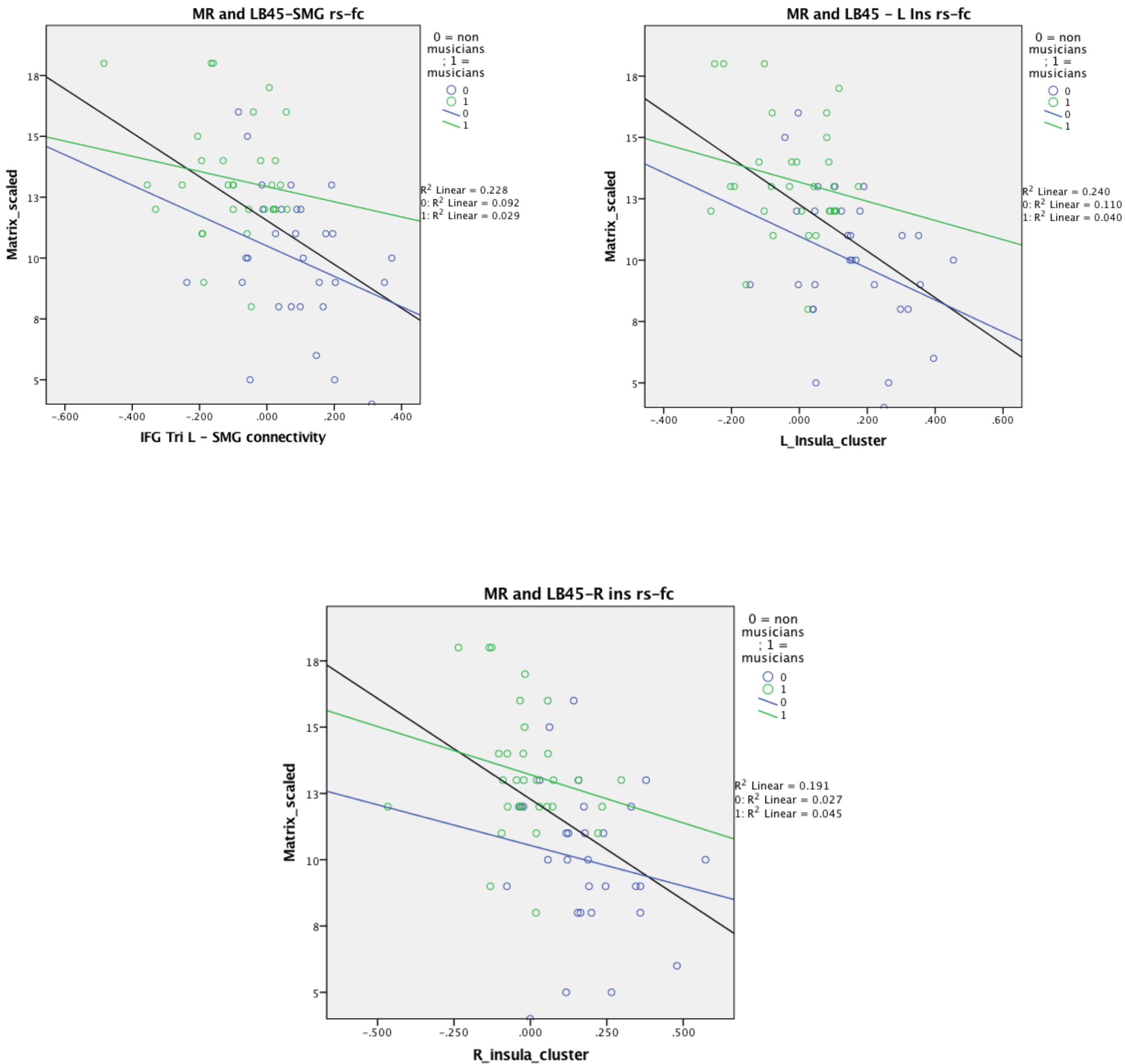


Figure 4. Correlations between the letter-number sequencing task and the rs-fc decreases between left IFG pars triangularis (LB45) and 3 separate brain clusters.

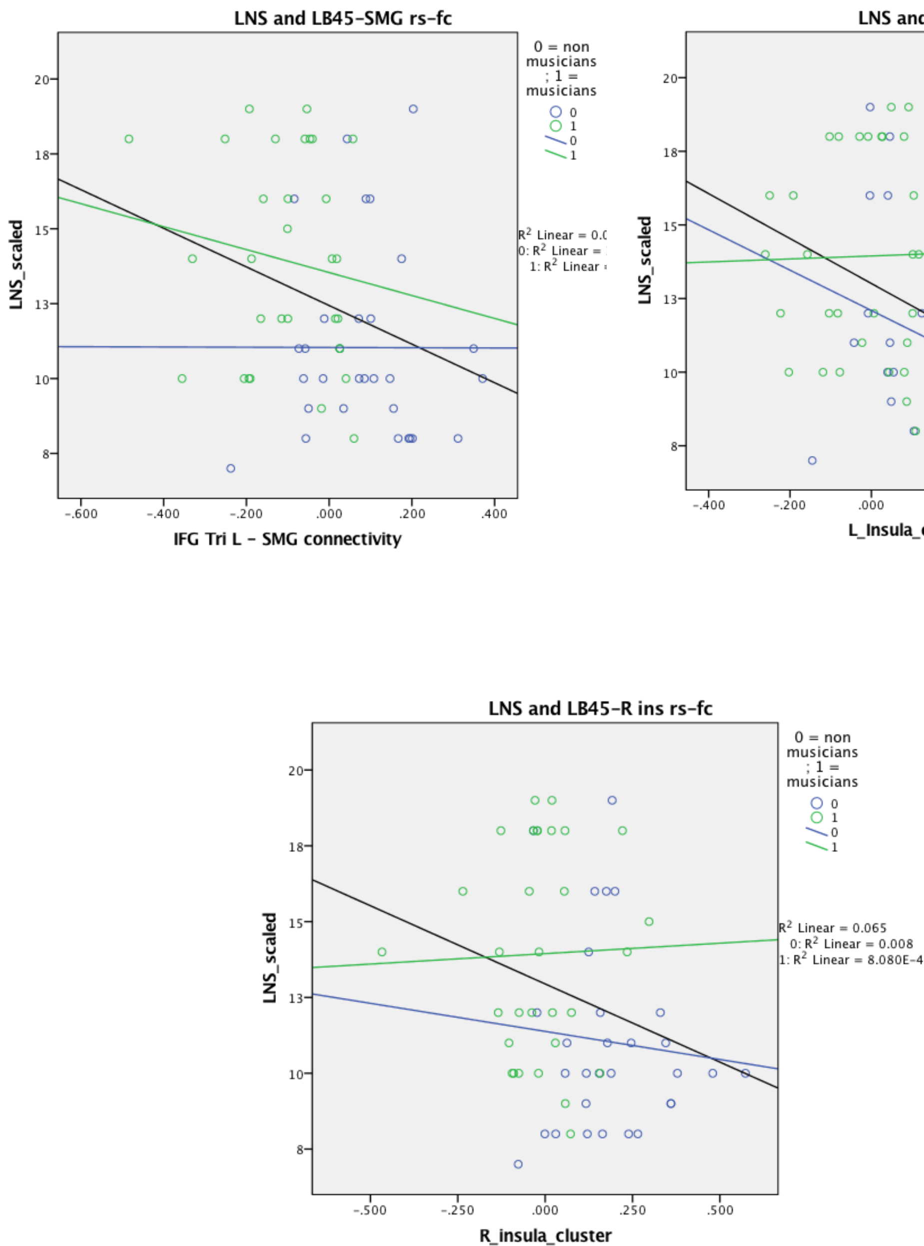
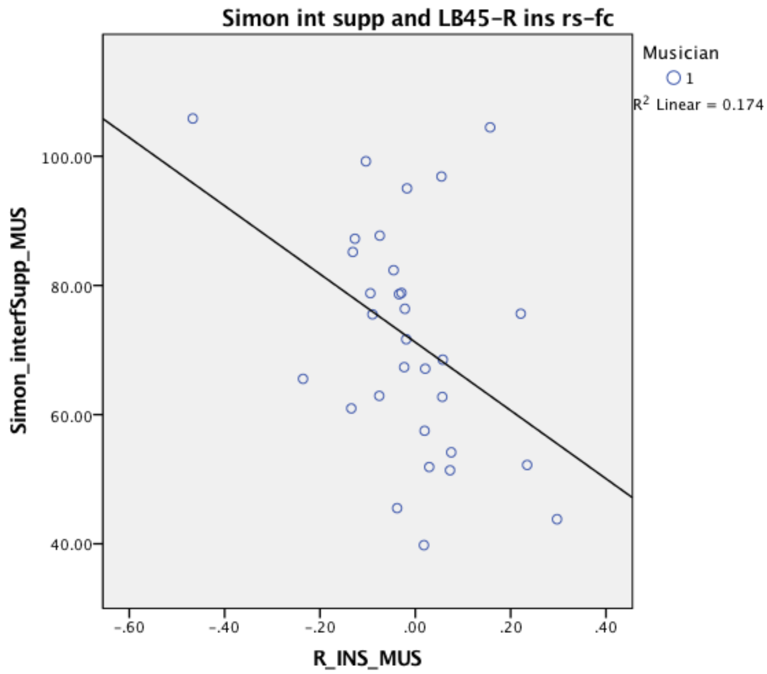


Figure 4. Simon Interference Suppression score and reductions in rs-FC between left IFG pars triangularis (LB45) and right Insula (R_insula) for musician bilinguals only



CHAPTER THREE: STUDY 2

Does dual training of musicianship and bilingualism result in enhanced non-native language perception and production abilities?

Abstract

Music training and speaking a second language both involve similar parameters important for their correct elicitation. These factors include comparable auditory features, overlapping brain networks, increased demand on attention and memory, and both necessitate auditory-motor integration. Due to these widespread similarities and, in particular, the neural overall and impact this has on other critical factors, there is suggestive evidence that musicianship may transfer to aspects of speech and language processing. In the current study, we recruited two groups of proficient bilinguals, with one group also being trained musicians. We were interested in examining a proposed "dual training" impact of possessing simultaneous experience across two similar and highly complex cognitive activities such as playing an instrument and speaking a second language on global cognitive functions, executive control and perception and production of foreign speech sounds. Despite not observing significant group differences on non-native language perception and production, we examined a series of significant correlations between reductions in rs-FC in a previous study (Gunther et al., 2021) and language tasks meant to assess accurate reproduction of foreign words and sentence. These findings lend further support to our previously proposed efficiency hypothesis by demonstrating that simultaneous experience with both music and bilingualism not only results in a more streamlined dorsal auditory-motor network, but also relates to accurate reproduction of heard NNL sounds. These findings add to our current proposal of a potential additive or dual-training effect musicianship combined with bilingualism.

Introduction

Music training and speaking a second language are both complex and demanding cognitive and sensorimotor activities. In fact, music and language share a number of important elements overall that are important for their mastery, including: sharing important auditory features, overlapping brain networks, enhanced attention and memory resources, and both require the integration of auditory and motor information (Patel, 2014). There is suggestive evidence that musicianship itself may contribute to global cognitive function (Schellenberg, 2004) and/or executive control (Schellenberg, 2005; Peretz et al., 2015). Very importantly, there is a robust line of current research demonstrating that musical training can specifically enhance certain aspects of speech and language processing including the ability to discern speech in noise (Parbery-Clark et al., 2013; Strait & Kraus, 2011), better phoneme and syllable discrimination (Zuk et al., 2013), better speech and auditory perception (Wong et al., 2007; Shahin et al., 2003), and enhanced reading fluency and literacy skills (for a review, see Gordon et al., 2015). The specific brain regions affected by both music and language experience are part of a shared network that includes the dorsal auditory stream, a circuit that plays a vital role in transforming the sounds we hear to the actions we produce (Hickok & Poeppel, 2007) resulting in a process known as auditory-motor integration. This overlap in brain regions important for both music and language production, organized in this dorsal stream, is believed to contribute to the potential transfer from musical training to certain aspects of speech and language (Patel, 2014). Despite this multi-faceted overlap in the critical elements inherent to music and speech, no research studies, to the best of our knowledge, have investigated the impact of mastering both these activities on cognitive and language skills. If music training can contribute to language skills, how does it compare to bilingualism? However, in our recent study described in Chapter 2, we found evidence for reduced rs-connectivity within the dorsal stream network for musician bilinguals compared to non-musician bilinguals. We interpreted this as evidence for greater efficiency in this network as a result of dual training. Therefore, the goal of the present study was to examine the potential additive or 'dual training' impact of expertise with both musicianship and bilingualism, on global cognitive functions, executive control and perception and production of novel speech sounds.

Transfer from music to language and other domains

In recent years, the neural overlap between music and language has been well-documented, as both involve similar functions and therefore share the brain regions that subserve these functions. When considering musicianship, for example, the changes taking place in the brain are likely a result from the fact that playing music is both a demanding and complex sensory-motor activity. Musicians need not only learn how to hierarchically time several precise actions, but also have to develop fine motor movements and learn to recognize various subtleties in pitch and sequencing simultaneously. Language is a congruently complex and demanding process that involves similar acoustic parameters, such as duration, intensity, frequency, timber, and so on. Overall, both processes involve a number of rhythmic and tonal features that require higher-order structuring to take place in order to process various sequences of acoustic events occurring simultaneously (for a review on overlap between both domains, see Peretz et al., 2015). Taken together, both music and language place significant demand on the auditory system of the human brain (Patel, 2014). According to Patel's OPERA hypothesis (2014), musical training itself may enhance various facets of speech processing due to the increased demand placed on sensory and cognitive processing, a mechanism shared by both music and speech. When this enhanced processing is combined with other factors such as reward, repetition, and the increased attentional resources necessary for both activities, this sets the stage for neural plasticity to occur, leading to long-term modification in brain function and structure that, in turn, may affect speech processing (Patel, 2014). In the current study, we were interested in examining the impact of this overlap on individuals who were both trained musicians as well as proficient bilinguals on both spontaneous functional connectivity across these overlapping neural networks as well as on a range of behavioural tasks tapping into cognitive measures, music, and speech.

Due to this large-scale and multi-faceted overlap, there is suggestive evidence that music skills may transfer to other cognitive domains, such as global cognitive function, memory, and, most notably, language (Moreno et al., 2011; Kraus & Chandrasekaran, 2010; Skoe & Kraus, 2013). In children, for instance, it has been shown that music lessons may contribute to increased aspects of global cognitive functioning including, verbal attention, executive function, and what is referred to as "full scale IQ," largely made up of tasks assessing such measures as verbal comprehension, perceptual organization, distractibility, and processing speed (Moreno et al., 2011; Schellenberg, 2004). Specifically, musicians have been shown to perform better on tasks that require elevated levels of executive functioning, such as memorization, attention, and higher level of cognitive control (Moreno et al., 2011; Kraus et al., 2014; Skoe & Kraus, 2013). This suggested transfer from music to various facets of cognition may be the result of prolonged periods of focused attention, mastery of fine-motor skills, and memorization of musical passages and structures (Schellenberg, 2004; Patel, 2014). Apart from studies outlining musical impact on global cognitive function, a body of research most relevant to our current study is focused on a potential transfer from music skills to various facets of language.

Studies within the field of the auditory cognitive neurosciences have demonstrated that music training modifies the auditory system in the human brain and effectively prepares musicians for a multitude of listening challenges that extend beyond the borders of processing music itself (Kraus & Chandrasekaran, 2010). Due to these reported enhancements, there is suggestive evidence that musicianship may have a positive transfer effect on various aspects of speech and language. For example, a crucial component is the development of the ability to recognize and consider concurrent and often competing sounds, including a broad number of stylistically diverse instruments and voices within a given piece of music. For a comprehensive review, a recent meta-analysis has summarized that music may lead to enhancements in reading readiness, phonological awareness, speech and auditory perception, and second language acquisition, to name a few (Gordon et al., 2015). Overall, Gordon (2015) posits that these overall literacy enhancements may be due to the fact that music training affects brain mechanisms that are important for both music as well as language cognition. Specifically, Parbery-Clark, Skoe, and Kraus (2009) demonstrated that trained musicians exhibited greater subcortical representations of speech sounds when these were paired with background noise, positing that extensive musical practice may result in enhanced neural coherence and an increased ability to perceive subtle speech sounds in otherwise noisy environments. Further, it has been shown that, when compared to non-musicians, people with musical training possess increased literacy skills (Tierney & Kraus, 2013), better phoneme and syllable discrimination (Parbery-Clark et al., 2012), and enhanced ability to detect subtle deviations in pitch contours in order to discern statements from questions (Magne et al., 2006)

In parallel with the multitude of research studies proposing a number of transfer effects from music to various aspects of speech and language, recent research has also demonstrated that musicianship may influence the perception and production of a foreign language (Chobert & Besson, 2013). For example, musicians have been shown to demonstrate quicker learning of implicit linguistic structures of artificial languages and may possess more robust representations of musical and linguistic structures overall, when compared to non-musicians (Francois & Schön, 2011). Further, musicians have also shown more accurate perception of subtle linguistic changes in a non-native language (Marques et al., 2007). In a recent study using a Hindi imitation task (Turker et al., 2017), it was shown that individuals with enhanced musical ability (measured by assessing rhythm and pitch discrimination, as well as considering number of instruments played) performed better on this non-native language imitation task. The authors posited that musicality may enhance phonetic coding ability, which they hypothesized is required in order to imitate unfamiliar language sounds. Tasks such as these have been used in previous studies with adults, with task performance shown to be related to brain structure in auditory and parietal regions that subserve both linguistic and musical functions (Schön et al., 2010). These studies demonstrate not only a transfer effect from musicianship to aspects of speech in general, but speech perception and production specifically. This particular facet of transfer was a primary variable that we tested in the current study.

In the resting-state study, we observed differences in resting-state functional connectivity within this dorsal-auditory network when examining a potential 'additive' effect of musicianship on top of bilingualism. Specifically, we observed that participants who were both proficient bilinguals and trained musicians, exhibited significantly decreased functional connectivity at rest between brain areas known to be critical for music and language processing (i.e., IFG, SMG/STG). In turn, we interpreted this reduction as representing greater 'neural efficiency,' with musicians potentially requiring a less extensive and more streamlined auditory-motor network as a result of a long-term, dual-training impact of mastering both an instrument and a second language. Music training has also been shown to induce plasticity within neural systems that also happen to be critical for the development of reading skills (Kraus et al., 2014). In the present study, we were interested in testing whether greater efficiency might result in greater transfer from music skill to foreign language perception and production.

In the current study, we were interested in examining whether long-term experience with bilingualism and music would result in enhanced sensitivity to aspects of unfamiliar foreign languages. Specifically, we sought to examine a proposed "dual training" impact on the participants' ability to perceive non-native language sounds and translate these sounds into action, effectively investigating auditory-motor links. In order to do so, we recruited two groups of bilinguals that rated themselves as being highly proficient, with one group also being trained musicians. Considering the proposed overlap between features of music and language, we hypothesized that the musician bilinguals would be more adept at perceiving subtle differences in non-native language tasks (hereafter referred to as NNL) such as the Hindi dental retroflex as well as being able to reproduce words and sentences in Hindi and Farsi in a more native-like way. We also sought out to explore the neuroanatomical correlates of these language tasks with resting-state functional connectivity reductions previously observed in the musician bilinguals in a companion study (using the same sample). This would allow us to investigate whether these brain differences would relate to overall task performance in a significant manner.

Methods

Participants

We recruited 62 bilingual participants who were divided into two groups: bilingual musicians who had greater than 10 years of musical training and were currently practicing their instrument (*n* = 31;M/F) and bilingual non-musicians who had less than 3 years of musical training and had not played in the last 5 years (*n* = 31; M/F). All participants spoke either

English or French as their second language (L2) and the large majority (84%) had English or French as their first language (L1). The bilingual musician and non-musician groups were matched on age, sex, years of second-language exposure (L2), number of languages fluently spoken, L2 verbal fluency (whether English, French, or other; see Table 1). Participants were recruited from the Department of Music at Concordia and McGill Universities, and from the general Montreal community. All were self-identified right-handers and had no known history of auditory, neurological or psychiatric disorder. Participants gave written informed consent. The research protocol was approved by the Concordia University Human Research Ethics Committee and by the Research Ethics Board of the Montreal Neurological Institute (MNI) of McGill University and was carried out in agreement with the principles of the Declaration of Helsinki.

Behavioural Measures

The musician bilingual group completed an extensive Musical Experience Questionnaire (MEQ) developed in our laboratory (Bailey & Penhune, 2010). From this questionnaire, we extracted three variables we believed to be most important in matching the groups where musicianship was concerned. Groups were compared on years of musical experience (total years involved in training and practicing music), years of formal training (total years enrolled in music lessons), and hours of current practice per week. Both groups also completed an in-depth language acquisition questionnaire (Marian, Blumenfield, & Kaushanskaya, 2007) and were compared on years of experience and daily usage of French.

Language proficiency

L2 verbal fluency, both phonemic and semantic, was assessed for all participants in either English or French, if they happened to speak the latter. For the English task, participants were asked to name as many words as they could think of beginning with the letter "A" and pertaining to the category of 'animals,' whereas the French task consisted of the letter "L" and the category 'fruits.' The participants responses were recorded, and scores were subsequently calculated by combining the total number of correct utterances. Participants were also asked to subjectively rate themselves on the number of languages they fluently spoke (scale of 1 to 7). In order for a language to be considered "fluent," the self-rated score had to exceed or be equal to 5.

Music tasks

Participants' musical abilities were examined using both the Rhythm Synchronization (Bailey & Penhune, 2010) and Melody Discrimination (Foster & Zatorre, 2010) tasks. The Rhythm Synchronization task requires participants to listen to and reproduce rhythms by synchronously tapping along on a computer mouse. We measured both the total percent correct (PC) of the participants' tap as well as the extent of their deviations from the interval between each pair of notes, referred to as inter-tap interval (ITI deviation). For the melody task, participants were asked to listen to two short sequences of melodies and indicate whether they were the same or whether they differed. The participants' performance was measured via a composite score comprised of correct responses on both simple and transposed melodies, collapsed into an overall percent correct score. A similar procedure was employed for a control (syllable discrimination) condition.

Cognitive tasks

Participants were tested on both the Matrix Reasoning and the Letter-Number Sequencing subtests taken from the WAIS-IV (Weschler Adult Intelligence Scale, Weschler, 2008). Scores from both tests were converted to scaled scores for analytical purposes. In order to examine executive function and cognitive control in the participants, we administered the Simon

Task (Bialystok et al., 2004); (Kousaie et al., 2014). This task contained four experimental conditions including: control, reverse, conflict congruent, and conflict incongruent. Participants were exposed to the 4 conditions 4 times each and the task was divided into two blocks, with each condition being presented twice in each block for a total of 48 trials altogether, in a fixed order. The specific measure focused on and included in our analyses was the "Simon interference suppression," which assessed the participants' ability to suppress interfering spatial information, calculated as an increase in response time for the conflict compared to the control condition (Kousaie, 2014).

Non-native language perception and production tasks

Hindi dental-retroflex discrimination task. This task required participants to learn to differentiate a synthetic version of the Hindi dental-retroflex contrasts ("da" vs. "dha") using a "perceptual fading" paradigm with three levels of difficulty (Goldestani et al., 2007). Participants were presented with a total of 7 stimuli varying in equal steps in terms of acoustic difference, from more to less distinct. Stimulus 1 corresponded to the dental voiced, unaspirated type ("da") and stimulus 7 to the retroflex type ("dha"). All of the stimuli were presented followed by the vowel /a/. For each trial, participants heard one of the phoneme types and were asked to determine which one they heard by pressing the corresponding button displayed on a computer screen (Figure 2.A). Visual feedback was given after every trial. For the first block of 20, only the largest differences between the sounds (stimulus 1 vs. 7) were presented. If the participant met the criteria for discrimination (16/20 correct), the subsequent block was comprised of a more constrained difference between the target sounds (stimulus 2 vs. 6; or 3 vs. 5). Training was discontinued once a subject either achieved criterion for the smallest contrast or once they completed a maximum of 200 trials (10 blocks). Performance on the phoneme discrimination task was computed as a global score that took into account the smallest perceived difference between the two phonemes and the number of trials. Specifically, participants started off with 600 points. An incorrect response resulted in -3 in the easiest condition, -2 in the next hardest condition, and -1 in the hardest condition.

Hindi Words and Sentence Repetition. This task required participants to listen to and then imitate 4 Hindi words and 4 complete Hindi sentences, the latter of which were comprised of different length and phonetic complexity and had previously been recorded by a native Hindi speaker (7/7/9/11 syllables long) (Reiterer et al., 2011a). Participants heard each sentence three times and then repeated the sentence once (Figure 2.B). Participants' responses were recorded onto a laptop by use of a microphone. Three native Hindi speakers rated the participants' responses. Raters scored the sentences on three parameters: Nativeness (how closely did the speech sample resemble native pronunciation), accuracy of the spoken sentence (how closely did the speech sample resemble correct utterance of the sentence considering rhythm and level of intelligibility), and prosody (taking into account stress and intonation patterns of the participants' utterances). Participants received a score for each word in the sentence (if a word was omitted, it received a 0). The average rating for that sentence was then calculated and averaged across the four sentences for each of the participants. Speech samples were rated blind to participant group and randomly ordered to prevent rater bias. This specific task was used in order to explore participants' performance on non-native language *perception*. Inter-rated reliability among the raters, measured using Cronbach's alpha, was 0.745 for words and 0.588 for sentences.

Phoneme and Word Reproduction Task. This task required participants to listen to and then imitate the Farsi voiced uvular stop /q/ in 12 different contexts (sound /q/ followed by 6 different consonant-vowel syllables and be 6 different bisyllabilic nonwords – Farsi words) (Goldestani & Pallier, 2007). Participants heard each word and syllable three times and then repeated it once. Participants' responses were recorded onto a laptop by use of a microphone. Three native Farsi speakers listened to and rated the participants' responses, providing a score on the overall variable "nativeness." This variable was operationalized as referring to how closely the participants utterances on the speech samples resembled correct utterances of the words and syllables considering rhythm and level of intelligibility. Speech samples were rated blind to participant group and randomly ordered to prevent rater bias. Inter-rated reliability among the raters, measured using Cronbach's alpha, was 0.799.

Rs-fMRI results. In the previous chapter, we observed converging rs-FC between musician bilinguals and bilingual non-musicians. Specifically, the former exhibited significant decreases in rs-FC between brain areas important for auditory-motor integration. For the specific findings that will relate to correlations observed with language variables in this chapter, see the methods and results section in chapter 2.

Results

Matching variables for musician and bilingual groups.

As our participants both differed in terms of musical experience and the age at which they acquired their second language, they were matched on a number of key variables in order to control for potential differences between groups. The musician bilinguals were compared with bilingual non-musicians using a one-way ANOVA across groups for age, years of musical experience, L2 verbal fluency (Table 1). As expected, musicians had significantly greater years of musical training. No other significant group effects were observed.

Cognitive tasks

Scores on both MR and LNS were in the normal range for both groups. One-way ANOVA for both tests showed that musician bilinguals significantly outperformed bilingual non-musicians (Table 2). Musician bilinguals also performed better on the *interference suppression* measure of the Simon Task (Table 2).

Language tasks

Hindi dental-retroflex discrimination task. One-way ANOVA for the Hindi perception task did not reveal a significant difference between groups on their ability to distinguish between the Hindi dental-retroflex contrast ($F(1, 59) = 2.319$, $p = 0.134$).

Hindi Words and Sentence Repetition. Cronbach's Alpha for the Hindi words and sentence repetition task was 0.745 for words and 0.588 for sentences. One-way ANOVA for the Hindi reproduction task did not reveal a significant difference between groups on the nativeness of their utterances on either the Hindi word reproduction ($F(1, 59) = 0.116$, $p = 0.735$) nor the Hindi sentence reproduction ($F(1, 59) = 0.983$, $p = 0.325$) tasks.

Farsi Phoneme and Word Reproduction Task. Cronbach's Alpha for the Farsi phoneme and word reproduction task was 0.799. One-way ANOVA for the Farsi reproduction task did not reveal a significant difference between groups on the nativeness of their utterances on phonemes and words globally ($F(1, 59) = 0.028$, $p = 0.867$). All language task values can be found in Table 3.

Correlations

Correlations with L2 and cognitive variables. No significant correlations were observed between performance on non-native language tasks and L2 (AOA L2, self-rated L2 fluency, verbal fluency in L2) or cognitive tasks (matrix reasoning, letter number sequencing, and Simon task).

Correlation between language tasks and music tasks. Across all participants, we observed that Hindi word nativeness was significantly positively correlated with percent correct (r(61) = 0.288, p = .024 and significantly negatively correlated with ITI deviation (r(61) = -.308, p = .016). Within-groups, only the musician bilinguals exhibited a significant positive correlation between Hindi word nativeness scores and percent correct (r(61) = 0.390, p = 0.030). The associated scatterplots can be found in figure 2.

Correlation between language tasks and rs-FC values. Across all participants, we observed a significant negative correlation between rs-FC of L B45 – SMG and Hindi word nativeness scores (r(61) = -0.283, p = 0.027) as well as a significant negative correlation between rs-FC of L B 45 – L insula and Hindi word nativeness scores (r(61) = -0.284, p = 0.027). A similar finding was observed between rs-FC of L B45 – SMG and Hindi sentence repetition scores (r(61) = -0.256, p = 0.047). In both cases, higher nativeness scores were related to decreased connectivity. The associated scatterplots can be found in figure 1.

When investigating within group differences, we observed a significant negative correlation for the musician bilinguals only between rs-FC of L B45 – SMG and Hindi word nativeness scores (r(30) = -0.355, p = 0.050). When examining within group differences for the bilingual non-musician group exclusively, we observed a significant negative correlation between rs-FC of L B45 – R insula and Hindi word nativeness scores ($r(30) = -0.387$, $p = .034$) as well as a significant negative correlation between rs-FC of L B45 – R insula and Farsi phoneme and word reproduction ($r(30) = -0.383$, $p = .037$). The within-group correlation scatterplots for the non-musician bilinguals can be found in figure 3.

Discussion

In the present study, we investigated whether there existed a dual training effect of musical expertise and bilingualism and the potential impact on auditory-motor links by testing whether musicianship may result in more native-like reproduction of foreign language sounds. We also sought to examine the neural correlates of these non-native language reproduction abilities by examining relationships between previously observed reductions in resting-state functional connectivity in brain areas organized in the dorsal auditory-motor stream and scores on Hindi and Farsi reproduction tasks. In order to do so, we recruited two groups of highly proficient bilinguals, matched on key demographic variables, with one group being comprised of trained musicians as well. Although musician-bilinguals did not show overall better performance on the NNL tasks, we did find a number of significant correlations between music skills and NNL reproduction as well as with previously observed reductions in rs-FC within the dorsal auditory-motor stream. Specifically, we demonstrated that the ability to reproduce foreign language sounds in a more native-like manner is associated both with reduced rs-FC between key brain areas involved in the transformation of auditory signals into motor action as well as performance on musical tasks. This particular result extends the finding in Study 1 (i.e., reduced rs-FC for musician bilinguals) 1 and lends additional support for the hypothesis of increased efficiency. Taken together, these results suggest that simultaneous expertise in both music and language results in a more streamlined or 'efficient' dorsal auditory-motor network, which in turn may increase one's ability to perceive and correctly reproduce not only musical sounds (i.e, tapping along to various rhythms) but facilitate the perception and accurate reproduction of NNL sounds.

Hindi Perception Task

Overall, we did not observe a significant difference between both groups on either the ability to perceive subtle differences in the Hindi dental retroflex contrast nor on one's ability to listen to and reproduce foreign language sounds in a more nativelike way. Previous studies investigating the ability to distinguish between this contrast have demonstrated mixed results. Previous studies employing this task have examined the relationship between non-native phonetic perception abilities (i.e., learning these unfamiliar speech sounds in a testing paradigm) and whether performance could be predicted particularly by white matter organization in the brain (Golestani et al., 2002). While there have been a number of structural studies, to the best of our knowledge, there are no studies investigating the functional connectivity correlates of the Hindi dental retroflex contrast task, nor have there been investigation of musician bilinguals. In effect, most experimental studies have examined either monolingual or bilingual performance on such a non-native phonetic perception task (Strange et al., 1989; Polka, 1989). For example, a study investigating monolingual individual's ability to distinguish between this contrast after 5 hours of training demonstrated that pre-training scores for non-native speakers were quite low. Other studies have provided up to 4 days' worth of training before testing the participants (Strange et al., 1989). In a study comparing English and Japanese participants' performance on the Hindi dental retroflex contrast, a dozen 30-minute training sessions were provided (Pruitt, 1995). When compared to our participants' scores and considering that our participants did not receive any training beforehand, the performance observed in our current study is comparable to previous findings. Perhaps a training phase may have helped to mitigate a ‘ceiling effect’ in the current study, effectively serving a ‘priming’ function, as previous studies have demonstrated significant improvement in performance following a training phase (Pruitt, 1995). Perhaps this may have allowed us to observe not only group differences on this perception task, but the potential neural correlates of a brief training phase on this experimental task that is itself difficult to perform. Then again, if we consider our main research question of whether an additive effect of musicianship over bilingualism would improve non-native phonetic perception, perhaps music does not provide an additional benefit over and above bilingualism. In any case, future studies could consider recruiting a group of solely monolingual individuals in order to investigate this proposed additive effect further, and perhaps consider implementing a training paradigm. In the present study, we did not observe significant global increases in nativity scores on any of our NNL reproduction tasks (i.e., Hindi words and sentences, Farsi phoneme and words) for the musician bilingual group. Future studies should consider recruiting a group of chiefly monolingual non-musicians which could allow for the investigation of whether bilingualism + music compared to solely bilingualism contributes significantly to NNL reproduction in a comparable fashion. In the current study, we were not able to acquire a set of data that would serve as a control. It is plausible that the addition of musicianship itself may not confer any added benefit or advantage over bilingualism, as both have been shown to exercise similar neural circuits and overlap in their proposed cognitive benefits. A monolingual control group may have allowed us to determine this with more certainty. Despite, previous compelling results have been obtained from studies opting to focus more prominently on the neural corelates of speech imitation rather than the imitation skill in and of itself. For example, a previous study has posited a distinct neuro-functional signature of speech imitation ability, with poor imitators also exhibiting the highest amounts of functional activation across a more widespread cluster of brain areas (Reiterer et al., 2011b). In this study, the participants who were rated as more nativelike in their reproduction of second-language imitation also possessed the greatest increase in GM and lowest levels of functional activation in left premotor areas including Broca's area. This result will be discussed further in a subsequent section on our own observed neural correlates of foreign language imitation.

Correlations Between Rhythm Tasks and NNL Tasks

Despite not having observed any global differences between groups on the language tasks, we observed a series of significant correlations that may support our working hypothesis of an additive impact of musical expertise on top of bilingualism and its potential effect on enhanced auditory-motor link when hearing and attempting to reproduce foreign language sounds (i.e, sound to action). The first significant correlation was comprised of enhanced performance on the rhythm reproduction task being significantly related to enhanced native-like reproduction of Hindi words between groups. It has been well documented (for a comprehensive review, see (Ladányi et al., 2020) that a shared network underlies musical rhythm abilities as well as the processing of speech and language. Due to this shared recruitment, research has demonstrated that individual differences (which includes global dysfunctions as well) related to rhythm processing may extend to speech and language deficits and disorders. In fact, Ladányi et al. (2020) explain that people with lowered rhythm processing abilities are more at risk for developing speech and language disorders. Importantly, the inverse is also true and is supported by a number of research studies demonstrating the positive transfer effects from musicality to aspects of speech, as referenced in an earlier section of the present study. Overall, this may be tied to the underlying neurological overlap important for accurate processing and performance related to both rhythm and language skills, as previously explored in the present study. Because music rhythm and speech processing share a number of well-defined underlying processes, a number of theories have emerged as a result (this includes Patel's (2014) OPERA hypothesis, also described in this paper). A more recent theory encapsulates the critical combination of elements important for music rhythm and speech processing, In a recent article, Fiveash et al. (2021) extend this theoretical outlook by proposing that there are three common facets of these theories that are integral to music rhythm and speech processing. These include: the theories consider fine-grained auditory processing as essential when considering important elements that explain why cross-domain transfer between both exist, neural oscillations are important for the structural processing of both music and speech signals, and sensorimotor coupling of musical rhythm and speech processing. Considering the latter point, this relates to one of our primary considerations for our own current working hypothesis of a transfer between both domains of music and language – auditory motor integration and the fact that motor areas of the brain are regularly recruited during the processing of both music (Chen et al., 2008) and speech (Glanz et al., 2018), Lastly, a recent in depth meta-analysis also demonstrates how the processing of musical rhythms relates to speech processing and reading skills (Gordon et al., 2015), thereby solidifying the importance of auditory-motor coupling when processing aspects of music and speech, and supporting the transfer between both. When considering this well-documented overlap in both music and language processes, it is not surprising that we observed a significant relationship between performance on tasks tapping specifically into musical rhythm skills and increased native-like utterances in the *production* of non-native language sounds (i.e., repeating words as more native-like). If the inverse is true – that deficits in musical rhythm processing may lead to language deficits, then observing the reverse in the present study may fit into the global scope of this specific overlap. As a result, this finding supports the overall idea that musical expertise itself contributes to hearing and then producing sounds (i.e., sound to action), and that a link between the ability to reproduce both musical rhythms and language sounds (which are both effectively rhythmic in nature) is plausible.

Correlations Between rs-FC and Language Tasks

We also observed a significant relationship between previously observed reductions in global rs-FC between brain areas organized within the dorsal auditory stream (specifically, L IFG pt – SMG/STG) and more native-like reproduction of both Hindi words and sentences. The dorsal stream brain areas that demonstrated reductions in in vivo functional connectivity in our previous study using the same sample are known to be organized in the dorsal auditory stream and are critical to linking sounds we hear to actions we produce. The IFG, which contains Broca's area, is comprised of two overarching subdivisions made up of the pars triangularis and opercularis. The former, representing the primary rs-FC finding in our study, is thought to contribute to higher cognitive function and plays a role in various language-related process including the production of speech, syntax, and semantic processing (Friederici, 2006.) In a translation study, the IFG pars triangularis was also shown to constitute a hub of the language control network that was associated with the ability to translate non-primary language sounds back to one's primary, native language. Therefore, this specific area may be important for listening to, comprehending, and reproducing a non-native language, and may extend to the current study's findings (Elmer, 2016). We therefore propose that these results may support a dual training effect of music and language may effectively result in enhanced auditory-motor interaction in musician bilinguals, which may facilitate accurate perception and, most importantly, reproduction of unfamiliar sounds.

Within Group Differences for Musician Bilinguals

An additional piece of evidence that supports our proposed dual training impact hypothesis of combined musical expertise and bilingualism relates to within-group differences across these significant correlations. We showed a series of significant correlations within the musician bilingual group's performance on the rhythm reproduction task and accurate reproduction of NNL sounds. Specifically, we demonstrated that the musicians who performed better on the rhythm reproduction task, as measured by a higher % correct score, were rated as reproducing Hindi words in a more native-like way. Furthermore, we also demonstrated that musicians who exhibited the greatest reduction in rs-FC between the L IFG pt and SMG/STG were also rated as reproducing Hindi words in a more nativelike way. These findings are interesting as they appear to fit with previous findings positing that neural networks involved in speech imitation have been reported in the left hemisphere and include the IFG, STG, Heschl's gryrus and the SMG (Vaquero, Rodriguez, & Reiterer, 2017; Catani et al., 2005; Kappes et al. 2010; Adank, 2012). These findings fit with the neural efficiency hypothesis that we proposed in Study 1 by demonstrating that long-term exercising of the network involved in musicality, which results in rs-FC decreases, is also associated with behavioural impacts as well.

Conclusions and Future Directions

The main purpose of this study was to examine whether having developed expertise across two intensive, sensori-motor domains such as musicianship and bilingualism would result in enhanced auditory-motor links represented by a greater ability to perceive and reproduce non-native language sounds in a more nativelike manner. Taken together, despite not observing global differences between both groups, we posit that the combination of both musical expertise and bilingualism may relate to one's ability to listen to and correctly reproduce NNL sounds, and that patterns of decreased rs-FC within the dorsal auditory-motor network also relate to these higher nativity scores. We believe that this reduction may be an index of neural efficiency, as put forth in further detail in Study 1. Furthermore, we also demonstrate the existence of within-group effects for musicians. Musician bilinguals who exhibited the greatest decrease in rs-FC within brain areas organized within the dorsal stream, also scored highest on musical rhythm tasks. This rs-FC reduction also correlated with enhanced ability to perceive and correctly reproduce unfamiliar foreign language sounds. This may suggest more enhanced auditory-motor integration as a result of simultaneous expertise of two highly complex and multi-faceted sensori-motor activities. The results also suggest that musicianship itself is a driving factor in these significant associations. Future studies that wish to extend this line of research examining a proposed dual training effect of developing expertise in both music and second language might benefit from recruiting a group of monolingual non-musician individuals in order to test whether musicianship contributes any global additive benefit when compared to chiefly monolingual individuals. It is possible that both bilingualism and musicianship confer similar advantages both neurally and behaviourally, and that the combined impact of being both musician and bilingual may not have any additional impact over and above solely possessing expertise with music. Recruiting a group of monolingual non-musicians would help clarify this possibility. Overall, these results suggest that simultaneous expertise in both music and language results in a more streamlined dorsal auditory-motor network, which may increase one's ability to perceive and correctly reproduce not only musical sounds, particularly musical rhythms, but may also facilitate the perception and accurate reproduction of NNL sounds.

Table 1

Demographic and Matching Variables of the Bilingual Non-Musicians (Bil NM) and Bilingual Musicians (Bil Mus)

	Mean age	Sex	Yrs edu	AOA mus train	Yrs mus	AOA L2	Yrs L2 exp	No. lang fluently spoken	Self-rated L2 fluency	Verbal fluency	Sim. bilingual	Seq. bilingual
Bil NM	25.03	12m 19f	14.06	11.33	1.25	9.57	19.19	2.00	5.98	25.37	9	22
Bil Mus	23.07	15m 16f	14.03	7.19	15.74	4.54	18.67	1.88	5.48	29.29	11	20
Sign.	n.s.		n.s.	P<.001	P<.001	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Table 2

Cognitive and Musical Variables in Bilingual Non-Musicians (Bil NM) and Bilingual Musicians (Bil Mus); (N = 62)

	MR	**LNS**	**Avg melody**	**Rhythm % corr**	**Rhythm ITI avg**	**Simon interference suppression**
Bil NM	9.97 (2.82)	11.03 (3.16)	61.83 (9.57)	0.73 (.074)	0.33 (.042)	91.44 (38.84)
Bil Mus	13.26 (2.42)	13.94 (3.43)	85.19 (4.76)	0.81 (.062)	0.25 (.058)	71.96 (17.99)
Sign.	P<.001	P<.001	P<.001	P<.001	P<.001	P<.015

Table 3

Language Task Performance in Bilingual Non-Musicians (Bil NM) and Bilingual Musicians (Bil Mus); (N = 62)

	Hindi dental retroflex	**Hindi word**	**Hindi sentence**	**Farsi**
Bil NM	353.03	54.12	31.84	29.96

	(64.66)	(10.27)	(7.86)	(9.99)
Bil Mus	384.35 (94.51)	55.02 (10.29)	34.38 (11.65)	29.57 (8.15)
Sign.	n.s.	n.s.	n.s.	n.s.

Figure 1. For all 3 correlation matrices, there is a significant whole group correlation. For the correlation between Hindi word nativeness and rs-FC of LB45/SMG, there is within group significance for the musician bilingual groups specifically

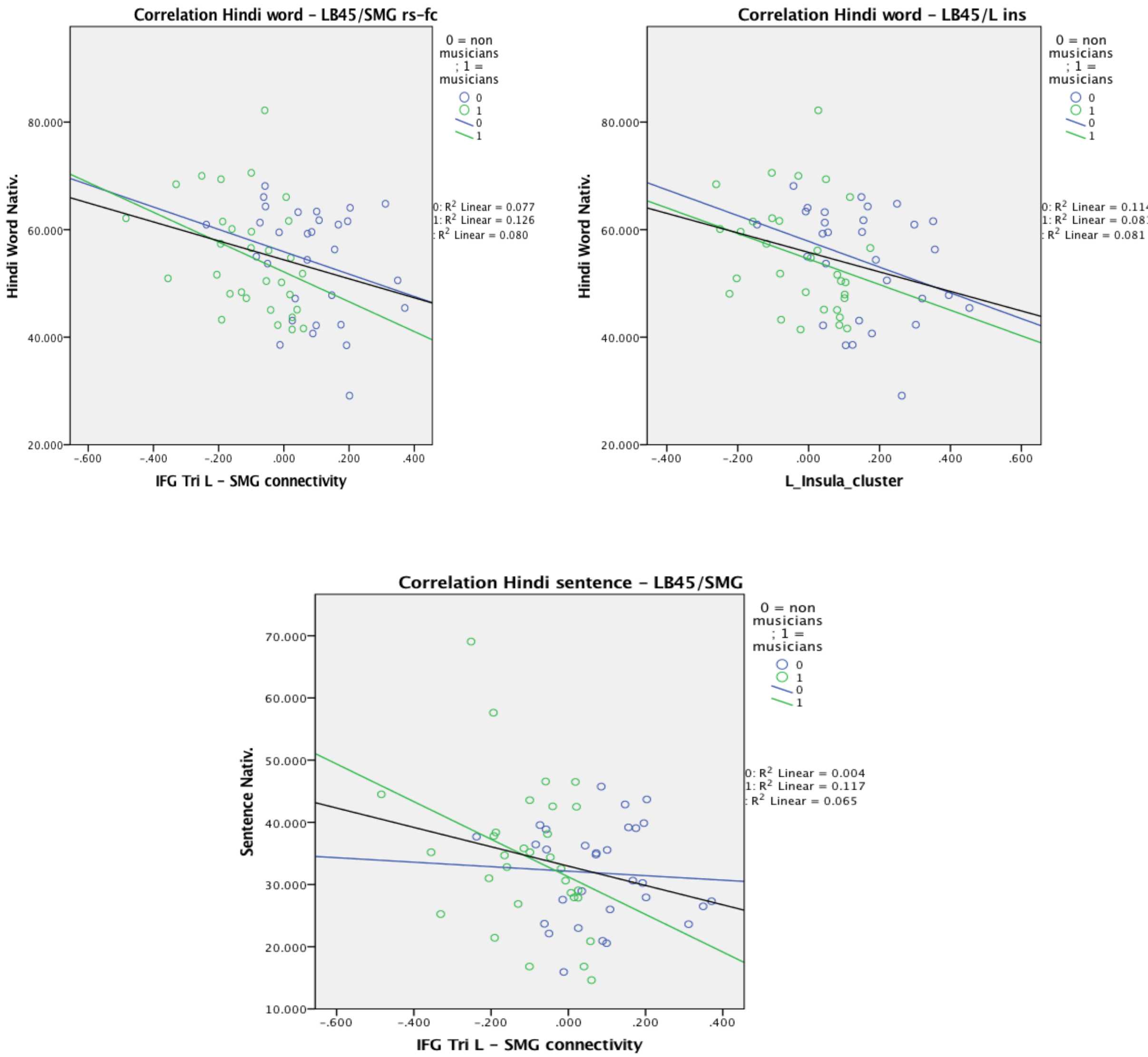


Figure 2. For all 2 correlation matrices, there is a significant whole group correlation. For the correlation between Hindi word nativeness and % correct, there is within group significance for the musician bilingual groups specifically

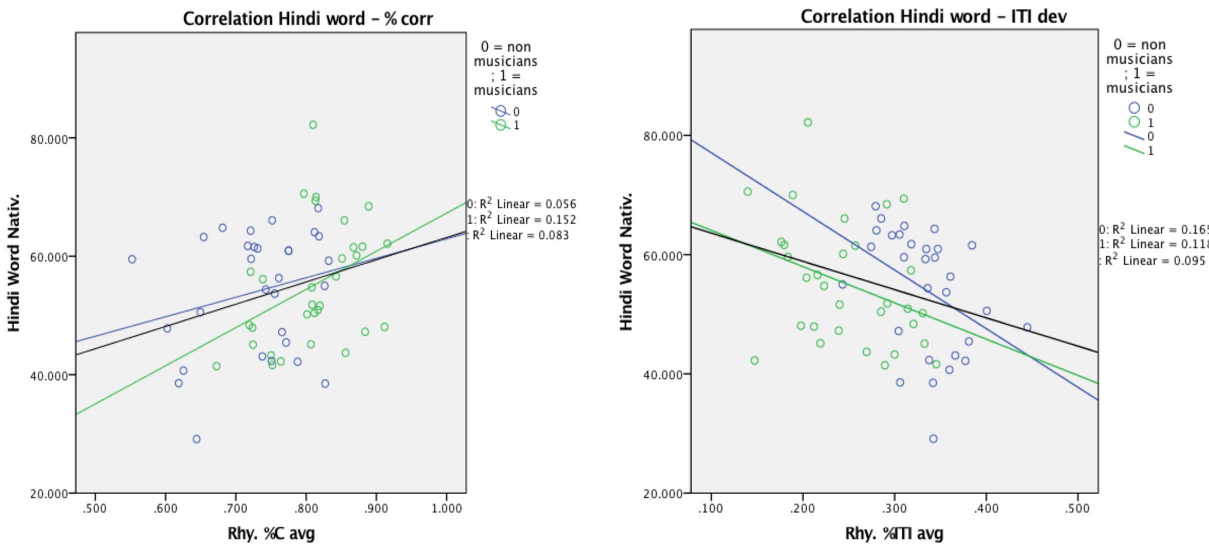
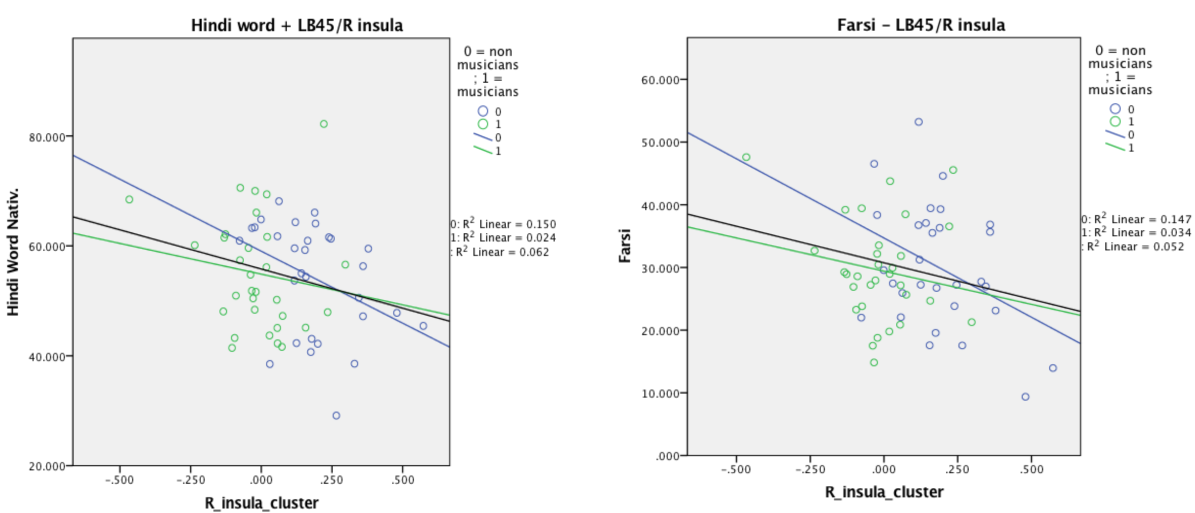


Figure 3. In the non-musician group specifically, there was a significant correlation between Hindi word nativeness and Farsi score on rs-FC between LB45 and R insula



CHAPTER FOUR: GENERAL DISCUSSION

Summary of findings

The primary goal of this thesis was to examine both the neural and behavioural consequences of possessing expertise across two highly correlated sensorimotor domains such as music and bilingualism. We were interested in examining whether this dual-training of being both a musician and bilingual would yield converging patterns of rs-FC in the dorsal auditory-motor stream, a network that has been shown to demonstrate considerable overlap for both activities. Behaviourally, we investigated if this dual training would confer advantages on cognitive tasks, music tasks, and tasks assessing perception and production of foreign language sounds. In order to test for a possible dual training effect of bilingualism and music, we recruited two groups of proficient bilinguals, with one group consisting of highly trained musicians (N = 31 in each group). We administered a battery of cognitive, musical, and non-native language tasks and all participants underwent rs-FC scanning. All participants were matched on key demographic and language variables that served as important controls.

Our primary objective in Study 1 was to investigate whether being both a trained musician and a bilingual would result in differing patterns of rs-FC in brain areas known to be organized within the auditory-motor dorsal stream. We hypothesized that the musician bilinguals would exhibit differing patterns of spontaneous brain activity within this circuit as a result of long-term dual-training on two tasks known to overlap in the neuro-anatomical networks important for their correct elicitation. As our participants differed in terms of their L2 age of start and overall musical experience, we controlled for a number of key demographics, musical, and language-related variables in order to reduce the likelihood of confounds and maximize our opportunity to observe true functional differences between the groups. The groups were matched in terms of age, sex, years of education, years of L2 exposure, number of languages fluently spoken, self-rated L2 fluency, and age of start of and total years of musical training.

We found that musician bilinguals exhibited significantly decreased rs-FC between the left IFG pars triangularis and three separate clusters comprised of the aSTG/SMG and bilateral insular cortices. Musician bilinguals performed significantly better on tasks of musical rhythm and melody discrimination, which was expected. We also found that musician bilinguals performed better on the interference suppression measure of the Simon task, which assesses the ability to ignore competing or conflicting information. A series of significant whole group correlations emerged between the decreases in rs-FC and cognitive task performance, with participants exhibiting the largest decreases in rs-FC also performing best on the Matrix Reasoning and Letter Number Sequencing tasks. In order to further examine and clarify musicianship's specific contribution to observed rs-FC changes, hierarchical regression analyses were conducted and revealed that musicianship was a unique incremental predictor of rs-FC above performance on the MR and LNS tasks. Taken together, these results lend support to our hypothesis of "neural efficiency" by demonstrating that possessing both musical and bilingual expertise, two tasks known to overlap in the neuro-anatomical pathways important for their production, may exercise this circuit over time, resulting in more efficient or streamlined spontaneous activity over time.

For study 2, considering the reductions in rs-FC observed in Study 1, we aimed to extend our hypothesis of enhanced network efficiency by investigating the impact of this dual-training on global cognitive functions, executive control, and perception and production of non-native speech sounds. We hypothesized that an additive effect may be present and that this would result in the participants possessing this dual experience of proficient musicianship and bilingualism being better able to perceive differences in the hindi-dental retroflex contrast when compared to their bilingual non-musician counterparts. We also hypothesized that the bilingual musicians would be better able to listen to and subsequently reproduce foreign language syllables, words, and sentences in a more native-like manner, when rated by native speakers of these languages. We also controlled for the same factors as in Study 1.

Contrary to our expectations, we did not observe any significant group differences on ability to distinguish between the Hindi dental-retroflex contrast nor on reproduction of Hindi words or sentences or Farsi phoneme and words. However, we did observe a series of significant correlations between previously exhibited rs-FC decreases and musical rhythm and language production variables. Specifically, we found that the most native-like reproductions of Hindi words were significantly related to decreases between the L IFG pt and SMG and L insula, and from Hindi sentence nativeness to L IFG pt and SMG. Further, within-group differences within the musician bilinguals themselves were found, with the greatest decreases in rs-FC between the L IFG pt and SMG being associated with higher nativity ratings on Hindi word reproduction. Finally, we also found that accuracy on the rhythm synchronization task was positively related to the most native-like reproductions of Hindi word. Overall, despite not observing global differences in perception or production scores, we found that the ability to reproduce foreign language sounds in a more native-like fashion was related to reduced spontaneous activity in brain networks vital for transforming auditory signals to motor action – regions known to be organized within the dorsal auditory-motor circuit. Taken together, we believe that these specific results add to our efficiency hypothesis initially proposed in Study 1. In this study, we provide evidence for a dual-training impact of both musicianship and bilingualism by demonstrating that the additive impact of musicianship may result in greater neural efficiency in networks critical for auditory-motor integration. We also demonstrate that this enhanced efficiency may relate to and facilitate accurate hearing of and subsequent reproduction of NNL sounds.

Situating our findings: Transfer of music to speech features

Our most compelling results demonstrated that combined music and bilingual experience resulted in decreased patterns of spontaneous brain activity within areas organized in the dorsal auditory-motor stream and key for auditory-motor integration, and that this connectivity is associated with the ability to listen to and correctly reproduce foreign language sounds. In this section, I will attempt to tie these results in with the global literature investigating functional connectivity as well as behavioural consequences of being a trained musician and a bilingual, as well as how these results may fit into hypothesis of music to speech transfer. Questions addressed will include: why would the addition of musical training result in *decreases* in rs-FC and why might these patterns of convergent rs-FC relate to cognitive, musical, and language variables.

A natural place to begin addressing these questions would be to review these findings through the lens of Patel's (2014) OPERA hypothesis and investigate whether our results fit within this model of transfer from music training to aspects of speech. The OPERA hypothesis posits that this transfer may exist but only if certain considerations are met. Primarily, there must exist an overlap in brain areas inherent to both music and speech processing. When this is combined with the emotional rewards of playing music, the frequent repetition inherent to long-term musical training, the sustained attention involved, and overall development of finely-tuned and precise motor movements, and if music places higher demands on these involved mechanisms, this may set the stage for musicality to positively impact the processing of speech.

Overlap

In the present study, we observed that bilinguals who were also trained musicians exhibited significantly decreased patterns of spontaneous functional connectivity between the left IFG pars triangularis and clusters comprised of the aSTG/STG and bilateral insula respectively. We selected seeds based on brain regions known to be implicated in not only music, but language as well. Our primary seeded region of interested was the IFG pars triangularis and opercularis, with the left IFG pt emerging as significant in its interaction with other regions including the STG and insular cortex. The IFG is a key node in the dorsal auditory-motor pathway which also includes auditory regions in the STG, articulatory and sensorimotor areas including the premotor, anterior insula, and temporo-parietal areas (Hickok & Poeppel, 2007). One of the reasons that functional connectivity between these regions may be modulated by combined music and bilingual experience is that the role of the STG within this pathway has been shown to relate to processing of complex sounds, including music and speech. In studies investigating the functional impact of hearing irregular musical chords, it has been shown that listening to such anomalies activated the IFG, STG, SMG, and insula (Koelsch et al., 2005). When considering the circuit or network formed by these structures, the authors posited that these brain areas may form a circuit that may play a role in a number of cognitive elements when it comes to processing musical sounds. It was also proposed that this network may play a role in processing musical syntax - or the "grammar" of music - auditory working memory, and possibly in the emotions elicited by music. Studies have also demonstrated that listening to music taps into such a circuit that includes the STG, inferior frontal gryri, as well as parietal and frontal areas (Janata et al., 2002). In this study specifically, attentively listening to music inside an fMRI scanner was shown to recruit this neural circuit, a circuit that also underlies other important higher-order cognitive functions such as attention, working memory, and semantic processing.

This is a good example of overlap between circuits that underlie both musical processes as well as other cognitive processes. When considering the STG and its role in this type of network, we know that it is involved in complex auditory processing and perception. In an article from 2002, Griffiths and Warren argue that the planum temporale, a large region that contains both the superior temporal plane and Heschl's gyrus, may act as a computational hub when it comes to processing intricate facets of audition. Griffiths and Warren (2002) offer an excellent summary of this area's involvement in processing diverse spectrotemporal patterns in music, including musical imagery, musical pitch perception, melodies in noise, listening to familiar pieces of music, and chord differentiation, to name a few. For speech, Griffiths and Warren explain that this large region is also implicated in a number of speech processing features (for a complete review, see Griffiths and Warren, 2002). Furthermore, concurrently activated specific regions also often include the STG, Heschl's gyrus, and insula. Relating this back to the dual stream hypothesis (Hickok & Poeppel, 2005) with a particular emphasis on the auditory dorsal stream, there is strong evidence that the network formed by these regions, as well as their individual functions, are implicated in musicality and speech and the overlap (as proposed by Patel, 2004) is quite clear.

Based on these observed results, with a particular emphasis on the neural overlap, we propose that the development of proficiency in both domains places great emphasis upon and simultaneously exercises these established neural circuits and may render them functionally more *selective* or *efficient* over time. In concert with this proposal, we observed decreased fc between the left IFG pt and the aSTG/SMG as well as the bilateral insular cortex. However, this model investigating modulated brain circuits also has implications for our behavioural findings as outlined in Study 2. Our behavioural findings comprised of significant correlations between musical rhythm and NNL reproduction can be seen through the lens of overlap and may relate to the overarching concept of a particular neural network that underlies rhythm and speech processing. In association with the rs-FC results observed in Study 1, this supports the primary hypothesis that a dual training impact may enhance auditory-motor interactions in people who are trained musicians and bilinguals. In turn, it is possible that this enhancement, which may result in enhanced functional selectivity in audio-motor networks, may play a role in listening to and reproducing unfamiliar speech sounds.

Precision, Emotion, and Attention

Along with the existence of shared neural overlap in auditory-motor networks vital for music and speech, Patel (2014) discusses four other critical components that may relate to transfer effects between both – precision, emotion, repetition, and attention. Considering their reciprocal nature of these and their relation to our findings, we discuss these components of the OPERA model collectively when interpreting our behavioural findings and how decreases in rs-FC relate to performance on our cognitive measures. In order to illustrate how these elements interact, let us consider the example of fingerpicking guitar as discussed in the general introduction of this thesis. This example is effective at demonstrating the reciprocal nature of the latter four elements found within the OPERA model and the subsequent discussion of our behavioural results will be framed through this lens. In order to accurately and clearly produce individual notes when fingerpicking, the motor movements must be incredibly precise. Repetition and hours of practice ultimately hones skill and fine-tunes performance, motor, and perception, as well as encoding of sound features (Patel, 2011). Further, finally being able to correctly play a practiced piece of music is very rewarding. The rewarding quality of music acts as a positive reinforcer for learning, enhances motivation, and elicits various emotions in the player. Studies have proposed that this reinforcement actually fine-tunes perception in order for the player to be able to perfect their performance (Mas-Herrero et al., 2013). Naturally, this reinforces the element of precision in turn. Lastly, through this entire process, a very selective, focused, and sustained attentional process is necessary. This example fits into the OPERA model, demonstrates the reciprocal nature of neural overlap, precision, emotion, repetition, and attention. Ultimately, the fingerpicking anecdote encapsulates the elicitation and importance audio-motor integration overall in playing using this particular technique.

Along with observing significantly decreased patterns of rs-FC connectivity for musician bilinguals in Study 1, our results also demonstrated that the addition of musicianship over bilingualism resulted in increased performance on cognitive tasks meant to assess global cognitive function, working memory, and cognitive control. A number of significant correlations emerged between performance on these tasks, as well as NNL tasks, and reductions in rs-FC between the groups. Why would engaging in long-term musical training as a bilingual produce such changes? This overarching question ties into the OPERA hypothesis (Patel, 2014). In addition to the neural overlap discussed above, precision, emotion, repetition, and attention are each important. A number of researchers (e.g., Patel, 2004; Kraus & Chandrasekaran, 2010) have opined that music training may affect language processing through higher level cognitive processes, such as attention and memory. For example, a recent research program looking to study transfer based on this hypothesis summarizes the influence that both working memory and attention have on these proposed transfer effects (Besson et al., 2011). In this program, the authors discuss both their results and interpretations. One primary resulted include that, when compared to non-musicians, musicians were better able to detect subtle variations in pitch violations. Further, with the interest of relating these latter 4 elements of the OPERA model to the neural overlap portion, researchers have also observed associations between cognitive task performance and fMRI differences in trained musicians. For example, it was shown that, not only did musicians outperform bilinguals and monolinguals on working memory tasks, but that musicians exhibited decreased levels of functional activity during the tasks in prefrontal gyrus and dorsolateral prefrontal areas when compared to controls (Alain et al., 2018). Importantly, the authors interpret these findings as potential signifying a more efficient use of neural resources, which is in direct correlation with our primary hypothesis of enhanced selectivity of efficiency as a consequence of music training and bilingualism experience. Overall, the interpretations put forth by these researchers parallel our own understanding of the current thesis' results. Music training involves multiple, simultaneous, complex auditory and motor parameters, including frequency, duration, attention, and memory. Long-term musical training may result in enhanced sensitivity to these parameters. Due to the neural overlap present in both music and speech (Patel, 2004; Kraus & Chandrasekaran, 2010), and considering this enhanced sensitivity in musicians, a musician's perception of these processes become more finely tuned over time, which in turn is what is thought to result in the proposed transfer from music to speech (Besson et al., 2011). This notion is also supported in other seminal studies as well, linked together by the proposal that long-term changes throughout the human auditory system as a result of intensive and consistent music training may in turn cognitively prime a musician to better perceive aspects of speech via higher-level cognitive processes (Gordon et al., 2015; Kraus & Chandrasekaran, 2010; Moreno et al., 2011). This exemplifies why studying musicianship represents a unique and fascinating way to explore neuroplastic changes in the human brain as a result of long-term training and expertise on a complex sensorimotor task.

Enhanced executive control in musicians

We observed that musician bilinguals were better able to disregard competing information in the Simon task, an executive control condition, when compared to bilingual non-musicians. Viewing this component yet again through the lens of the OPERA model, it is possible that this constitutes an additional impact of musicianship over bilingualism. Long-term musical training strongly taps into complex sensori-motor criteria as outlined in the OPERA hypothesis. Simultaneously, speaking two languages already results in a natural necessity to disregard competing information due to switching back and forth between two languages of expertise. As a life-long bilingual myself, I can attest to the fact that this is sometimes challenging and may result in the uniquely Quebecois phenomenon of speaking "*Franglais*," particularly in a bilingual environment such as Montreal, QC, Canada. Despite this potentially enhanced ability to disregard conflicting information, is it possible that the addition of musicianship over bilingualism provides yet another layer of skill when this ability is concerned? Closely akin to our own studies, a recent study investigated the potential additive effect of musicianship on top of bilingualism by examining performance on the Simon task by comparing bilinguals, musicians, and bilingual musicians (Schroeder et al., 2016). Overall, their results found no differences between bilingual and monolingual musicians on the Simon interference suppression task. The researchers suggested that perhaps bilingualism itself may allow an individual to attain the "upper limit" of interference suppression, with the addition of musicianship providing negligible benefit. In a highly related recent study, musicians were also shown to perform better than bilinguals and monolinguals on aspects of executive function including skill at task switching and dual-task performance (Moradzadeh et al., 2015). However, the addition of musicianship over bilingualism in this study was not shown to provide any added benefit over and above simply being a musician. It is important to note that an overarching finding in one of our research studies did suggest that musician bilinguals may possess enhanced ability to suppress interfering information when compared to solely bilinguals, and that this performance may be related to diverging patterns of rs-FC in the dorsal stream. It is suggested that bilingual individuals experience these aforementioned cognitive enhancements in an organic fashion throughout development, as they must actively engage in interference suppression when processing language in order to prevent the non-targeted language from interfering when their intention is to use the target language itself (Schroeder, Marian, Shook, & Bartolotti, 2015). A recent study examining the specific roles of musician and bilingualism demonstrated that music training and speaking a second language play a different role on brain networks that support executive control function. Despite exhibiting comparable performance on a no-go task, bilinguals and musicians were shown to differ in their neuronal responses (Moreno et al., 2014). Another similar study demonstrated that, while musicianship and bilingualism resulted in enhanced executive control as measured by performance on the Simon task, the addition of musicianship over bilingualism did not provide any added benefit. Tying this back to the results that were observed on the interference suppression component of the Simon task – that musician bilinguals were better able to disregard competing information – it is possible that there may be an additive effect when musicianship when this particular skill is added to speaking two languages, although future studies should consider recruiting a group of monolinguals as it is possible that the benefit of musicianship supersedes that of bilingualism. In our current study, it was difficult to disentangle the true impact of musicianship without either a monolingual group or a monolingual musician group in order to examine the impact of solely musicianship.

Tying this avenue of research back to the neural overlap readily observed between music and language, it has been suggested that enhanced cognitive control (and specifically increased ability on interference suppression in bilinguals) reflects the diverging patterns of connectivity in brain regions important for this cognitive control. Importantly, bilinguals have been shown to exhibit more functional 'efficiency' within the dorsal anterior cingulate cortex, characterized by reduced activation, while outperforming monolingual individuals on tasks assessing language control and nonverbal conflict resolution. It has been posited, once more, that expertise gathered from lifelong use and practice of two languages may "reshape" the brain and result in modulated brain activity. In this respect, it was reported that this bilingual brain development might play a role in helping these individuals recognize behavioural incongruencies and aid in resolving cognitive conflicts on these cognitive tasks (Abutalebi et al., 2012).

Limitations, considerations, and future directions

One of the main limitations of the current thesis was not having a monolingual non-musician group of participants that would have served as a comparison group. Unfortunately, we were in the process of actively recruiting and testing such a group when the COVID-19 pandemic began in March 2020. It would have been interesting to observe such a group and add a supplemental layer of analyses to our primary 'additive effect' hypothesis in order to test whether such an effect would be present from monolingual non-musician, to bilingual, to bilingual musician. At the same time, this may have allowed us to disentangle our lack of significant findings on the NNL tasks between bilinguals and musician bilinguals. For the language tasks specifically, the recruiting of a monolingual non-musician group could have allowed us to examine whether the addition of musicianship over bilingualism might not result in a significant impact above and beyond the impact already provided by speaking two languages fluently. In terms of the cognitive task, based upon previously observed results, it would have also been beneficial to examine the impact of bilingualism and musicianship, as the only factor at play, on Simon task performance. As our musician group were also bilinguals, it would have been advantageous to test a group of musician monolinguals in order to directly examine the impact of musical training exclusively. Therefore, future studies should consider recruiting such a group in order to add to clarify musicianship's role when music training is added to bilingualism. Overall, one primary consideration when contemplating these limitations and future directions is the inherent difficulty of making comparisons between complex functions such as musical training and bilingualism, particularly considering their multi-faceted overlap. In the current study, we strived to control our groups on key variables in order to reduce the possibility of external confounds. Despite, it remains that our groups did differ in areas that are difficult to control. For example, it was difficult to acquire a purely homogenous group of French/English individuals in a multicultural and multilingual city such as Montreal. As a result, a number of our participants had a primary language that was not English nor French. Further, a number of our participants reported being familiar with a third language. Another point of consideration is whether transfer effects might differ between tonal and non-tonal languages. As a number of our participants reported speaking Mandarin Chinese, this would be an interesting point to consider for future studies. Finally, we were not able to consider the type of musical training that individuals reported, nor whether there may exist an impact of the instrument type reported by the participants. Therefore, future studies could consider these nuances when recruiting groups similar to the participants in the current study.

Moreover, future studies could consider investigating the impact of age of start of musical training or the impact of simultaneous vs sequential bilingualism. Studies from our lab have shown that early-trained musicians (beginning music training before age 6) demonstrate differing patterns of structural and functional connectivity as well as increased performance on music and cognitive tasks compared to individuals who began musical training after the age of 7. In a companion study using the same data set, it was found that simultaneous bilinguals exhibited enhanced leftward symmetry of the arcuate fasciculus (Vaquero et al., 2017). The arcuate fasciculus is known to act as a bridge between the STG and IFG. As our specific functional results demonstrated that the addition of musicianship over bilingualism resulted in significantly decreased spontaneous activity between the left IFG pt and the aSTG/SMG, it would have been interesting to observe whether the age of start of musical training can further modulate in vivo activity within this audio-motor circuitry.

Rs-FC analysis strengths

Resting-state fMRI is a method of examining intrinsic correlated activity across brain regions. Brain regions whose activity is highly correlated are thought to be engaged in functionally-specific networks, and the correlations across regions are thought to be influenced by factors such as training, experience, or disease state (Lewis et al., 2009). As we were interested in specifically examining differing levels of connectivity within established auditory-motor brain networks, using rs-FC as our primary analytical method conferred this benefit in the current study. There are certain reported advantages to utilizing resting-state fMRI compared to traditional task-based fMRI, especially when examining the consequences of mental illness on the brain. More generally, resting-state fMRI has been described as an advantageous technique as it circumvents performance related confounds such as movement in the scanner. Moreover, it is relatively easy to implement, lower-cost, non-invasive, and benefits from greater availability when compared to task-based fMRI. Resting state fluctuations in the BOLD signal of fMRI have also been reported to result in good signal to noise and requires patient compliance to be minimal. It can even be implemented while a patient is under anesthetic (Fox & Greicius, 2010).

Summary of Interpretations and General Conclusions

We propose that our observed results therefore appear to fit into the literature on transfer effects from music to language and network efficiency. Specifically, we observed that our musician bilingual group displayed enhanced ability on tasks assessing global cognitive and executive functions including working memory and the ability to disregarded irrelevant information in an experimental paradigm. This is in line with previously discussed research examining global cognitive enhancements as a result of musical training. We also propose that reductions in rs-FC patterns may result from long-term engagement in two highly complex and similar sensori-motor activities across time. We interpret these results as meaning that this may create a more selective auditory-motor circuit herein interpreted as “enhanced efficiency” or “selectivity” as a result of simultaneous exercising of the dorsal auditory-motor. Importantly, these reductions in rs-FC were also found to relate to these skills as well as the ability to listen to and correctly reproduce NNL sounds. These overall results appear to fit into transfer hypotheses such as OPERA (Patel, 2014), both satisfying the neural overlap component and demonstrating that musicians not only show improvements across behavioural variables but that these improvements are also related to these brain changes.

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