Exploring the Relationship between Prosodic Production, Brain Structure and Functional Connectivity in the Bilingual Brain

By: Jasmine G. Lee
Integrated Program in Neuroscience
McGill University, Montréal, QC
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Abstract

While many aspects of the neurobiology of language have become less elusive over the years, the neural bases of prosody remain controversial. Prosody refers to the melody and rhythm of speech, and includes prosodic cues such as fundamental frequency (F_0) and duration (Dogil et al., 2002). Due to the variation in the use of these cues across languages, mastery of the production of prosodic cues in multiple languages is a difficult task, which is only possible given sufficient language exposure and experience (Gilbert et al., 2019). The current study investigated the brain structure and functional connectivity that supports mastery of prosodic production in English-French bilinguals. A prosodic production task was used to determine participants' mastery of the prosodic cues of F_0 and duration across both English and French. Participants' production of F_0 and duration were then used as the behavioural measure in correlations with data from Voxel-Based Morphometry (VBM) and seed-to-voxel resting state functional connectivity analyses. Findings from the current study illustrate the role of the basal ganglia and the cerebellum in prosodic production in both English and French. VBM analyses illustrated a dissociation between these prosodic cues, with native-like F_0 being associated with gray matter volume (GMV) in the bilateral basal ganglia while native-like duration was associated with GMV in the left cerebellum in both languages. Functional connectivity analyses showcased a potential subcortico-cortico-cerebellar network associated with native-like production of prosody across both languages. Interestingly, functional connectivity analyses also identified the supramarginal gyrus as implicated in this prosodic production network, with increased functional connectivity between the supramarginal gyrus, the basal ganglia and the cerebellum being associated with more native-like production of both F_0 and duration cues in both languages. Although the basal ganglia and the cerebellum have not traditionally been directly associated with language, results from the

current study add to the growing body of literature illustrating the role of these regions in language processing, and in prosodic production specifically. Notably, the novel findings are also the first in the field implicating a potential network for prosodic production.

Résumé

À travers les années, plusieurs enigmes de la neurobiologie du langage ont été clarifiés, mais les bases neurales de la prosodie restent controversées. La prosodie fait référence à la mélodie et au rythme de la parole, et comprends des indices prosodiques tels que la fréquence fondamentale (F_0) et la durée (Dogil et al., 2002). La prosodie linguistique étant spécifique à chaque langue, la maîtriser dans plusieurs langues est une tâche longue et difficile qui n'est possible qu'avec une expérience suffisante dans chaque langue (Gilbert et al., 2019). Le projet actuel examine la structure cérébrale et la connectivité fonctionnelle qui soutiennent la maîtrise de la production prosodique chez les personnes bilingues. Une tâche de production prosodique a été utilisée pour déterminer le degré de maîtrise atteint par les participants dans les indices prosodiques de F_0 et de durée, en anglais et en français. La production de F_0 et de durée par les participants a ensuite été utilisée comme mesure comportementale pour la morphométrie à base de voxel (VBM) et les analyses de connectivité fonctionnelle. Les résultats de l'étude actuelle illustrent le rôle des ganglions de la base et du cervelet dans la production prosodique en anglais et en français. Les analyses VBM ont identifié une dissociation entre ces indices prosodiques, avec le F_0 associé au volume de matière grise (GMV) dans les régions sous-corticales bilatérales, et la durée associée au GMV dans le cervelet gauche dans les deux langues. Les analyses de connectivité fonctionnelle semblent indiquer l'existence d'un réseau sous-cortico-cortico-cérébelleux associé à la production de prosodie native dans les deux langues. Notamment, les analyses de connectivité fonctionnelle ont aussi impliqué le gyrus supramarginal (SMG) dans ce réseau de production prosodique, avec une connectivité fonctionnelle augmentée entre le SMG, les ganglions de la base et le cervelet étant associée à la production native des indices prosodiques de F_0 et de durée dans les deux langues. Bien que les ganglions de la base et le

cervelet n'aient pas traditionnellement été directement associés au langage, les résultats de l'étude actuelle s'ajoutent à la littérature illustrant le rôle de ces régions dans le langage, et particulièrement dans la production prosodique. Notamment, les nouvelles découvertes sont les premières dans le domaine impliquant un réseau potentiel pour la production prosodique.

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Contributions

The current study was a subset of a larger collaborative project titled the Montreal Bilingual Brain Initiative (MoBI). As such, the prosodic production task was designed by Dr. Annie Gilbert, Dr. Inbal Itzak and Dr. Shari R. Baum. The neuroimaging aspect of the experiment was designed by Dr. Denise Klein. Collection of all MRI data and most behavioural data was conducted by Dr. Shanna Kousaie, with the remaining behavioural data collected by Kristina Coulter. Behavioural prosodic production data was analyzed by Haruka Saito and Dr. Annie Gilbert. The voxel-based morphometry (VBM) analyses were conducted by Dr. Shanna Kousaie, and the resting state functional connectivity analyses were conducted by Jasmine Lee. The interpretation of results was completed by Jasmine Lee, under the supervision of Shari Baum and Denise Klein; the dissertation was written by Jasmine Lee, and all tables and figures were created by Jasmine Lee (with the exception of VBM figures, which were created by Dr. Shanna Kousaie).

Glossary

AF/SLF	Arcuate and superior longitudinal fasciculus
AoA	Age of acquisition (for the second language)
BA	Brodmann area
ECF	Extreme capsule fasciculus
EEG	Electroencephalography
ERP	Event-related potential
F_0	Fundamental frequency
FDR	False discovery rate
GMV	Gray matter volume
HLHQ	Health and language history questionnaire
IPL	Inferior parietal lobule
L1	First (i.e. native) language
L2	Second language
MLF	Middle longitudinal fasciculus
MRI	Magnetic resonance imaging
rTMS	Repetitive transcranial magnetic stimulation
rs-fMRI	Resting state functional magnetic resonance imaging
SMG	Supramarginal gyrus
t-fMRI	Task-based functional magnetic resonance imaging
VBM	Voxel-based morphometry
WAIS	Wechsler adult intelligence scale

Introduction

While many aspects of the neurobiology of language have become less elusive over the years, the neurolinguistics of prosody remain controversial. Despite extensive research in the field, the specific brain regions involved in the processing of prosody remain a point of debate. There have been opposing findings regarding the lateralization of prosody as well as the key brain regions involved, as increasing evidence highlights the potential that regions outside of the cortex (e.g., cerebellum, basal ganglia) may be playing a pivotal role in prosodic production (Belyk & Brown, 2013; Casini & Ivry, 1999; Dogil et al., 2002; Heisterueber et al., 2014; Marien & Manto, 2016; Paulmann et al., 2008; Sammler et al., 2015; Sammler et al., 2018; Schirmer et al., 2001; Witteman et al., 2011). While most research has focused on monolinguals, there have been relatively few studies investigating these issues in bilinguals. Consequently, it remains even more unclear which brain regions may be linked with mastery of production and perception of prosody in a second language (L2).

Prosody refers to the melody and rhythm of speech, and is present in all speech, making it a key facet of spoken language. It includes three primary prosodic cues, namely fundamental frequency (F_0), duration and amplitude (Dogil et al., 2002; Sammler et al., 2015; Wildgruber et al., 2006). These three main prosodic cues can be manipulated at various levels of an utterance (e.g. lexical, phrasal) in order to convey information about the utterance beyond the literal words spoken, such as designating emotion (e.g. anger, sadness) in the case of emotional prosody, or word segmentation, lexical stress and sentence focus in the case of linguistic prosody (Belyk & Brown, 2013; Ladefoged, 2001). These linguistic prosodic cues are essential for understanding language, as in order for anyone to be able to extract meaning from language, one must first be able to break down the speech stream into its component parts (e.g. sentences, words). Naturally, this is relatively easy in written language, given that the boundaries between words and sentences are clearly illustrated using spaces, commas and periods. However, the boundaries are not as clear-cut in spoken language. Instead listeners must make use of a variety of acoustic cues in the speech stream, such as cues about linguistic prosody, in order to effectively segment spoken language into words and sentences (Cutler et al., 1989).

The use of these prosodic cues for linguistic prosody follows a language-specific structure, whereby speakers of different languages use the same prosodic cues following different segmentation patterns (Belyk & Brown, 2013; Cutler et al., 1989; Dogil et al., 2002; Spring et al., 2013). For example, English speakers use prosodic cues at both the lexical and the phrasal levels, whereas French speakers only use prosodic cues at the phrasal level (Cutler et al., 1989). This in turn leads to differences in the way that listeners of English and French segment the speech stream in their respective languages. This cross-linguistic variation is evident in English words such as "content" which have different meanings based on changes in word stress (e.g. CONtent vs. conTENT), a distinction which is not used contrastively in French. Due to this contrastive stress, native French speakers tend to have difficulty identifying these types of distinctions when learning English, a phenomenon which has been termed 'stress deafness' (Dupoux et al., 1997). Since the majority of words in English begin with a stressed syllable, stress can serve as an indicator of the potential presence of a new word in the speech stream (Cutler & Carter, 1987). For this reason, English listeners typically use a trochaic (strong-weak or stressed-unstressed) stress pattern to locate word boundaries in an utterance (Spring et al., 2013). Unlike English, French is a syllable-timed language without lexical stress, and for this reason, French listeners typically use a syllabic segmentation pattern, which largely ignores lexical stress (Spring et al., 2013). Instead they tend to focus more on syllable structure to identify boundaries in the speech stream, primarily using syllabic lengthening of final syllables to identify boundaries at offsets of words, phrases or sentences (Tremblay et al., 2012).

Interestingly, monolingual speakers seem to apply the segmentation pattern that is characteristic of their native language when listening to speech of any language. For example, Cutler et al. (1986) found that when listening to the same English stimuli, monolingual French speakers relied on the syllabic segmentation pattern that is characteristic of French, whereas monolingual English speakers used the trochaic segmentation pattern that is characteristic of English. This illustrates how monolinguals are limited to the prosodic segmentation pattern that they have acquired from birth. However, the case of bilinguals is more complex and not fully understood. There have been debates in the field as to whether bilinguals are able to attain native-like mastery of prosodic cues in their two languages. Initial research on this question suggested that bilinguals are limited to the segmentation strategy of one of their languages, arguing that there are limits on bilingualism (Cutler et al., 1989; Cutler et al., 1992). Following this argument, bilinguals were thought to be limited to the speech segmentation strategy of their dominant language (the language in which the bilingual is most proficient). Often bilinguals' dominant language is their native or first-learned language. However, for bilinguals who acquire both their languages from birth and who have maintained high proficiency in both languages across their lifespan, language dominance is not as obvious, instead referring to the language in which they are subjectively more comfortable. Cutler et al. (1992) tested bilinguals with more than one native language to investigate whether having multiple native languages affects speech segmentation. The participants had acquired both French and English from birth and continued to use both languages on a daily basis. These individuals were so proficient in both languages that they were rated as "native-like" in both languages by native speakers of each respective language. Their language dominance was determined using self-report of which language each participant preferred to use. Cutler et al. (1992) found that neither English-dominant bilinguals nor French-dominant bilinguals were able to master the prosodic segmentation strategy of their non-dominant language. Specifically, the English-dominant bilinguals never used syllabic parsing patterns in either language. The French-dominant bilinguals were able to refrain from using syllabic parsing patterns for English stimuli, but were not able to use the trochaic parsing typical of English. In contrast, more recent work suggests that given enough experience in each language, bilinguals are able to switch between speech segmentation strategies (Goetry & Kolinsky, 2000, Spring et al., 2013). The growing consensus is that given sufficient language exposure and experience, it is possible for bilinguals to adapt and switch between the prosody of multiple languages. Various studies have highlighted many aspects of bilinguals' second language experience that play a pivotal role in mastery, such as the age of acquisition (AoA) of the second language and the amount of exposure the bilingual has had to the second language (Kim, 2019; Trofimovitch & Baker 2006). Interestingly, some studies reported that bilinguals did not always use the segmentation strategy that matched the language of the conversation. Instead, the language in which the bilinguals were primed (i.e. had been using prior to the conversation of interest) was often found to be the best predictor of the speech segmentation strategy used by the bilinguals (Namjoshi et al., 2012; Spring et al., 2013). Therefore, the bilinguals were not always able to perform identically to monolinguals in each language, as they did not always switch to the segmentation strategy that matched the language they were using at the time. Moreover, work by Kim (2019) examined heritage speakers of Spanish on their prosodic perception and production. These individuals grew up hearing Spanish at home but never fully learned the language, and had lived in a community where Spanish was rarely spoken. As such, Spanish was a non-dominant native language for them, providing novel insight into effects of language dominance and native languages on speech segmentation. Kim (2019) found that these heritage speakers were able to outperform Spanish second language (L2) learners on a perception task involving stress identification in Spanish, performing comparably to monolingual Spanish speakers on the task. However, the heritage Spanish speakers were limited in their production and were only able to perform at the level of the Spanish L2 learners. This suggests that with earlier and increased exposure to both languages, bilinguals are able to attain native-like prosodic cue perception, but not production. This illustrates the pivotal role of language experience in shaping bilinguals' mastery of prosody. Moreover, a recent study from our lab supports these findings, showcasing how language experience factors may be key to prosodic mastery in French-English bilinguals (Gilbert et al., 2019). Given this growing consensus, the current study aims to investigate this issue within the context of the underlying brain structure and functional connectivity that may be supporting this mastery of prosody across languages in bilinguals.

1.2 Prosodic Processing in the Cortex

There remains some debate as to which brain regions are principally involved in prosodic production. Although language is traditionally associated with the left hemisphere, the lateralization of prosody has been more controversial. An early and long-standing theory is referred to as the functional lateralization hypothesis, which proposes that the lateralization of prosody varies depending on its function. Following this, emotional prosody is argued to be processed in the right hemisphere whereas linguistic prosody is processed in the left hemisphere (Van Lancker, 1980; Van Lancker et al., 2006). An alternative theory proposed by Van Lancker & Sidtis (1992) hypothesized that the brain would break down the prosodic input according to prosodic cue (e.g. F_0, duration) rather than by type of prosody (e.g. emotional, linguistic). As such, it was thought that the brain regions associated with prosodic processing would differ depending on the prosodic cue, meaning that the function of prosody (e.g. emotional, linguistic) would have no effect on the manner in which it was processed. However, later tests of this theory were unable to find supporting evidence (Pell & Baum, 1997). More recent work has proposed the acoustic lateralization hypothesis, suggesting that both hemispheres work in conjunction for prosodic processing with short term changes in prosodic cues at the segmental or lexical level processed in the left hemisphere, and global changes in suprasegmental prosodic cues processed in the right hemisphere (Wildgruber et al., 2006). Similarly, in a review paper, Witteman et al. (2011) reported that damage to either hemisphere could lead to impairments in either linguistic or emotional prosody, but that greater impairments in linguistic prosody were associated with damage to the left hemisphere whereas greater impairments in emotional prosody were associated with damage to the right hemisphere (in keeping with the original functional lateralization hypothesis (Van Lancker, 1980)). Therefore, it appears that there may be a relative but not absolute left hemisphere lateralization for linguistic prosody.

Within each hemisphere, using task-based functional magnetic resonance imaging (t-fMRI), prosodic processing has been linked to traditional language areas in the cortex, such as Broca's area (Brodmann areas [BA] 44 and 45 in the inferior frontal gyrus [IFG]) (Dogil et al., 2002). Within the IFG, the right hemisphere pars opercularis (BA 44) and pars triangularis (BA 45) have been associated with production of linguistic prosody, a finding which is inconsistent with the functional lateralization hypothesis (Belyk & Brown, 2013; Domahs et al., 2013; Van Lancker, 1980). Interestingly, a recent review of various t-fMRI studies found that the bilateral pars orbitalis (BA 47) has been associated with emotional prosody rather than linguistic prosody (Belyk & Brown, 2013). Importantly, given the artefacts commonly produced as a result of spoken language production in an MR environment, the majority of neuroimaging prosodic processing studies have focused on perception of prosody. With regard to more broad, non-prosodic aspects of language, the left pars triangularis has been associated with cognitive elements of speech production, such as verbal and semantic retrieval, while the left pars opercularis has been linked to the higher-level motor aspects of speech production (Petrides, 2014; Sprung-Much & Petrides, 2018). Notably, the pars opercularis is directly adjacent to the motor (BA 4) and premotor (BA 6) cortices, and it has been proposed that these regions work together for language production, with the pars opercularis functioning as an interface between the motor control and cognitive aspects of language, linking the pars triangularis and the premotor and motor cortices (Petrides, 2014; Sprung-Much & Petrides, 2018). Neurological stimulation studies with humans found stimulation of the pars opercularis to be a reliable cause of speech arrest (Breshears et al., 2015; Penfield & Rasmussen, 1949). Therefore, the pars triangularis and opercularis have been strongly associated with language production and prosody specifically.

With regard to the network of brain regions involved in processing prosody, little is known and only a couple of studies have investigated this issue although with prosodic perception rather than production (Sammler et al., 2015; 2018). Prosodic pathways have been hypothesized in the right hemisphere, linking the IFG and Superior Temporal Gyrus (STG), regions traditionally associated with prosodic processing (Aleman et al., 2005; Domahs et al., 2013; Klein et al., 2011; Wildgruber et al., 2006). These prosodic pathways are thought to mimic those observed in the left hemisphere for non-prosodic aspects of language (Sammler et al. 2015; 2018). In the left hemisphere, the dorsal pathway is thought to be implicated in the motor aspects of speech, connecting the superior temporal to premotor regions via the arcuate and superior longitudinal fasciculi [AF/SLF] (Petrides, 2014; Saur et al., 2008). The ventral pathway is thought to extract meaning from speech sounds, connecting the temporal lobe with the inferior frontal gyrus via the extreme capsule fasciculus [ECF] (Petrides, 2014; Saur et al., 2008). Work by Sammler et al. (2015; 2018) provided evidence from t-fMRI, diffusion weighted imaging and fiber tractography that there are both dorsal (via the AF/SLF) and ventral (via the middle longitudinal fasciculus [MLF]) pathways in the right hemisphere that are linked to emotional prosody. As such, it has been argued that the right hemisphere's IFG and STG are the main brain regions playing a pivotal role in prosody, and that the IFG and STG may be working in tandem via these pathways. Notably, the stimuli used in Sammler et al.'s (2015; 2018) task investigated global changes in prosodic cues, and as was expected following the functional lateralization hypothesis detailed above, were processed in the right hemisphere. Since prosodic pathways for linguistic prosody remain largely uninvestigated, it has yet to be determined whether the findings from Sammler et al. (2015; 2018) are reflective of all prosody or of emotional prosody alone. Given that the functional lateralization hypothesis states that linguistic prosody would be processed in the left hemisphere, it follows that the analogous fiber tracts in the left hemisphere may play a pivotal role for linguistic prosody.

1.3 Prosodic Processing Beyond the Cortex

Interestingly, a series of studies have pointed to areas outside of the cortex that may also play a role in prosodic processing, particularly the basal ganglia and the cerebellum. Although these regions have historically been associated with motor functions such as movement and coordination, they have been increasingly linked to cognitive functions, particularly language. Various theories have been proposed as to the nature of the basal ganglia's role in language. Damasio (1983) first hypothesized that the basal ganglia may play a modulatory role on cortical areas involved in language processing. Since then, there has been increasing evidence to support this theory. Notably, it has been proposed that the basal ganglia serve a domain-general function in cognitive processing, which happens to include language processing (Kotz et al., 2009). Following this theory, the basal ganglia work as a pacemaker, synchronizing internal and external events with the cortex. It was suggested that while this includes non-linguistic stimuli such as musical beats, it also includes linguistic stimuli, such as speech (Kotz et al., 2009). The conditional routing model of the basal ganglia by Stocco et al. (2010) advances this notion, proposing that the basal ganglia receives signals from across the cortex, before modulating, integrating and synchronizing the signal to then redirect it back to the appropriate region of the cortex. Accordingly, the basal ganglia have been found to be connected anatomically to motor, pre-motor and frontal regions of the cortex (Lehericy et al., 2004; Bitan et al., 2005). It has been thought that the basal ganglia may be implicated in articulatory control and phonological segmentation via these connections with the cortex (Bitan et al., 2005, Booth et al., 2006). Booth et al. (2006) examined processing during a (phonological) rhyming task using t-fMRI and dynamic causal modelling, and found unidirectional functional associations from the putamen to both the left IFG and the left lateral temporal cortex. The authors proposed that these findings showcase how the putamen of the basal ganglia may be modulating articulatory or phonological output, and as such may be working in tandem with cortical regions involved in phonological processing, namely the left IFG and the left temporal cortex (Booth et al., 2006). Notably, the left hemisphere basal ganglia have also been associated with prosody, albeit emotional prosody (Paulmann et al., 2008). Paulmann et al. (2008) found that patients with left hemisphere basal ganglia lesions were impaired in their recognition of emotional prosody as compared to healthy controls, using electroencephalography (EEG). The basal ganglia have also been linked to bilingualism. Klein et al. (1994, 1995, 2006) found the left putamen to be associated with production of speech in a bilingual’s second language, thought to be due to greater articulatory demands. Work by Abutalebi et al. (2013) using t-fMRI further found the left putamen to be associated more specifically with language production in a low proficiency second language, with minimal involvement of the left putamen for production tasks in a high proficiency second language. The authors also found structural differences using voxel-based morphometry (VBM), having observed greater grey matter volume (GMV) in the left putamen of trilinguals with a high proficiency non-native language as compared to monolinguals. They hypothesized that these structural differences were reflective of the trilinguals' mastery of a large articulatory repertoire spanning across multiple languages (Abutalebi et al., 2013). This was further supported by findings from Berken et al. (2016) showing that the timing of second language acquisition was associated with differences in GMV in the left putamen, with simultaneous bilinguals showing greater GMV in the left putamen than sequential bilinguals; Berken et al. (2016) also found that sequential bilinguals with accents that were rated as highly "native-like" had greater GMV in the left putamen as compared to less "native-like" sequential bilinguals. This illustrates the role of the basal ganglia in bilingualism and articulation of speech. More recent work using t-fMRI also suggests a potential link between the basal ganglia and language control in bilinguals, arguing that the basal ganglia may mediate signaling to the prefrontal cortex (PFC) in accordance with the language used by the bilingual at any given point in time (Seo et al., 2018). Similarly, the left caudate has been associated with language switching in bilinguals across bilinguals of various languages (Zou et al., 2012; Price et al., 1999).

Furthermore, work with patients also highlights the role of the basal ganglia in language. Interestingly, there have been a wide array of neurological conditions that have potential links to prosodic impairments. One such example is Parkinson's disease (PD), a degenerative disorder linked to the basal ganglia, that leads to motor and sensory deficits, with some deficits linked to speech impairments. Many patients report impaired articulation of speech, namely reduced F_0 variability in speech production (Macoir et al., 2013). Notably, patients with Parkinson's also are impaired in their sensorimotor learning, including speech production (Mollaie et al., 2016). During an altered feedback speech production task for the prosodic cue F_0, PD patients were observed to overcompensate in their production of F_0 as compared to healthy controls, which the authors hypothesized may be due to the somatosensory impairment observed in PD patients. This further exemplifies the role of the basal ganglia in speech production, showing that sensorimotor impairments can in turn lead to fine grained impairments in production of specific prosodic cues, such as F_0.

Similar to the basal ganglia, the cerebellum has also historically been associated with motor control, movement and coordination. Nonetheless it has been increasingly implicated in other cognitive functions, namely language. Growing research has been conducted to discriminate more specifically which aspects of language are associated with which subregions within the cerebellum. A recent review has found language to be associated with the right lobules VI and VII, as well as Crus I and II of the cerebellum (Vias & Dick, 2017). Interestingly, bilateral lobules IV - VI have been associated with articulation of speech sounds, and have been functionally linked to the cortex in studies of healthy controls and patients with lesions to these regions (Marien & Manto, 2016; Marien et al., 2014; Vias & Dick, 2017). Results from Booth et al. (2006) using t-fMRI and dynamic causal modelling found reciprocal interactions between the cerebellum and the cortex, specifically the left IFG, and the left lateral temporal cortex. Notably, these reciprocal interactions appear to be largely contralateral, mostly linking the right cerebellum and the left cortex (Marien & Manto, 2016; Vias & Dick, 2017). For this reason, it has been suggested that the cerebellum may be an exception to the traditional view that language processing is lateralized to the left hemisphere (Muller & Meyer, 2014). Since there have been few studies on prosodic processing in the cerebellum, it remains to be seen whether the debatable lateralization of prosody will have an effect on the lateralization of the cerebellar regions involved. Nonetheless, given the contralateral connections described above, and following the functional lateralization hypothesis of prosodic processing, it follows that the left cerebellum may be linked to the right cortex for emotional prosody, while the right cerebellum may be linked to the left cortex for linguistic prosody.

A subcortico-cortico-cerebellar network for processing aspects of speech related to timing has also been proposed (Heisterueber et al., 2014). As part of this network, the cerebellum is thought to work in conjunction with the basal ganglia as well as the cortex, specifically the bilateral IFG, insula, precuneus, pre-SMA and SMA. Nonetheless, there remains some debate as to the specific subregions of the cerebellum that may be playing a key role. Notably, some of the variety in subregions implicated may be due in part to the variation in language tasks investigated. For example, Heisterueber et al. (2014) found that processing of word-stress related prosody was associated with activity in the left Crus I and the right lobule X of the cerebellum. Alternatively, Muller & Meyer (2014) used resting state functional magnetic resonance imaging (rs-fMRI) to examine general language networks in the brain, and found a link between the left IFG (specifically BA45) and the right cerebellum Crus I. Furthermore, Booth et al. (2006) found activation in the right cerebellum lobules VI and Crus I during a phonological rhyming task, as well as bidirectional connectivity between these regions and the left IFG as well as the left temporal cortex. As such, the variation in the aspects of language tested may account for some of the variation seen in the literature as to which specific subregions of the cerebellum may be linked to the cortex for language processing.

Various studies in patients with cerebellar damage have observed that these patients experienced prosodic impairments, among other symptoms. Parsons et al. (2009) found that patients with cerebellar lesions were impaired on F_0 discrimination tasks as compared to healthy individuals. This is also supported by work on patients with cerebellar ataxia (due to cerebellar lesions), who were found to have impaired F_0 discrimination, but preserved duration discrimination (Marien et al., 2014). However, other researchers have found that patients with cerebellar lesions have impaired duration discrimination, and poorer accuracy on perceptual tasks involving timing (Casini & Ivry, 1999). Although these studies have linked prosodic processing of both F_0 and duration to the cerebellum, it remains unclear as to whether both prosodic cues are equally associated with the cerebellum, or whether specific subregions of the cerebellum are preferentially engaged in prosodic processing for each prosodic cue. Moreover, it remains unclear whether any deficits found are specific to the perceptual as compared to the production modality. Another example of this is ataxic dysarthria, a motor execution disorder wherein patients with cerebellar damage have impaired speech production, with prosodic impairments such as speech timing, pitch, voice quality or volume being extremely common (Marien et al., 2019). The speech production impairments observed in ataxic dysarthria are thought to reflect physical (motor) difficulties in coordination of the orofacial muscles involved in speech production (Marien et al., 2019). Due to the specificity required to produce native-like speech, minute differences in motor coordination of the orofacial muscles can lead to perceptually large differences in the sound produced, which in cases of patients have been observed to lead to discrepancies between the intended and produced speech production. Notably, this also relates to bilingualism and healthy controls. Due to the different use of prosodic cues across languages, bilinguals may also be undergoing sensorimotor learning to master native-like production of prosody in a second language. However, there is a lack of research in this area with regard to bilinguals and cross-language variation, an issue addressed by Pinto et al. (2017) in an opinion paper. As the majority of studies from the literature focus on monolingual English speakers, it is unclear whether the observed effects would hold true across all languages, or whether bilingualism would lead to differing findings. This potentially limited generalizability further clouds the literature on prosodic processing and its relationship to the basal ganglia and the cerebellum.

1.4 The Current Study

Broadly, the proposed study aims to (1) investigate brain regions associated with mastery of prosody at the structural and functional network levels and (2) identify whether there are differences in these brain regions and networks related to use of bilinguals' first or second language. More specifically, a key aim of the study is to examine in what way the basal ganglia and the cerebellum play a role in prosodic production, and in what way these brain regions work in tandem with traditional language areas, as increasing evidence suggests (Booth et al., 2006; Marien et al., 2014; Marien & Manto, 2016; Muller & Meyer, 2014; Seo et al., 2018; Stocco et al., 2010).

Previous work in the field largely focused on task-based fMRI studies, usually investigating monolinguals, or comparing monolinguals and bilinguals. However, this fails to address the differences between bilinguals that drive some bilinguals to a stronger mastery of prosodic systems of both their languages. The current study aims to explore this issue by recruiting exclusively bilinguals, allowing for comparison across bilinguals to determine whether any differences in brain structure or functional connectivity are associated with a stronger mastery of prosodic production.

Performance on a prosodic production task was analyzed in conjunction with neuroimaging findings to investigate the brain structure and functional connectivity that may be supporting native-like prosodic production across two languages. In order to examine both the structural and network levels, two task-independent neuroimaging methods were be used: anatomical MRI for structural Voxel-Based Morphometry (VBM) analyses, and resting state (rs-fMRI) for network-level functional connectivity analyses. Crucially, given the difficult and prolonged nature of achieving native-like mastery of linguistic prosody across multiple languages, these task-independent methodologies provide a more nuanced analysis than a traditional task-based analysis, allowing for insights into how the brain has been shaped by mastery of two languages. More precisely, the current study aims to focus on whether there are any differences in brain structure and functional connectivity that may be underlying mastery of two systems of linguistic prosody. Notably, these task-independent neuroimaging methods also avoid artefacts commonly observed in t-fMRI language production studies, which often occur as an undesired side effect caused by the movement necessary to articulate speech sounds (Dogil et al., 2002).

Core hypotheses:

1. Bilinguals who have attained more native-like prosodic production in their languages will show greater grey matter volume in the cerebellum (right lobule IV - VII, Crus I) and the basal ganglia (left putamen) following previous work by Abutalebi et al., 2013; Berken et al., 2016; Klein et al., 1994; Marien et al., 2014; Marien & Manto, 2016.
2. Bilinguals who have attained more native-like prosodic production in their languages will show increased functional connectivity between these regions (i.e. right cerebellar lobule IV - VII, Crus I, left putamen) and the traditional language regions in the cortex (i.e. left inferior frontal gyrus pars triangularis and opercularis, as well as premotor and motor

cortex) building on findings from Belyk & Brown, 2013; Booth et al., 2006; Marien et al., 2014; Marien & Manto, 2016; Muller & Meyer, 2014; Petrides, 2014; Stocco et al., 2010; Vias & Dick, 2017.

3. There will be greater involvement of the basal ganglia (left putamen) and cerebellum (right lobule IV - VII, Crus I) in bilinguals' second language as compared to their first language, due to lower proficiency and greater articulatory demands (Klein et al., 1994; Abutalebi et al., 2013; Seo et al., 2018; Marien & Manto, 2016).

Methodology

2.1 Participant Information

Ethics approval was obtained from the Research Ethics Board at the Montreal Neurological Institute at McGill University. Participants provided written consent before completing the study. A total of 15 (11 female; 4 male) participants were included in the current study. All were English-French bilinguals who had learned English as a first language (L1). Participants were either simultaneous bilinguals (who acquired both languages from birth, n = 9) or sequential bilinguals (who learned their L2 at a later age, n = 6). The sequential bilinguals had acquired their L2, French, between the ages of 3-10 years old, with an average age of acquisition (AoA) of 5.67 years old. The average age of participants at the time of testing was 23.93 years. For a summary of participant demographic information, see Table 1 below. Participants completed a behavioural testing session, as well as both anatomical and resting state functional magnetic resonance imaging scans.

Table 1: Summary of Participant Demographics

	All participants	**Simultaneous bilinguals**	**Sequential bilinguals**
Number of participants	15	9	6
Age of acquisition of the second language	3.09	0.00	5.67
Age at the time of testing	23.93	23.66	24.33
Gender (female/male)	11/4	5/4	6/0
Years of formal education	15.46	15.22	16.00
Matrix Reasoning Score (WAIS)[1]	20.33	20.77	19.66

[1] Out of a maximum score of 26

2.2 Behavioural Testing Session

Participants first completed a pre-screening phone interview to assure eligibility. Only bilinguals who spoke Québecois French and Standard Canadian English were recruited to avoid dialectal variability. Exclusion criteria included fluency in a third language, musical experience, vision or hearing impairments, as well as any history of brain trauma or neurological disorders. During the testing session, participants completed a Health and Language History Questionnaire (HLHQ; full version in Appendix), which was based on the *Language history questionnaire* (LHQ 2.0, Li, Zhang, Tsai, & Puls, 2013). Participants were right-handed, as determined by the Edinburgh Handedness Inventory (Oldfield, 1971; see Appendix). Intelligence was also tested using the matrix reasoning subtest of the Wechsler Adult Intelligence Scale (WAIS), with the average score being 20.33 out of 26 (Table 1). The matrix reasoning subtest in particular was chosen for its focus on nonverbal reasoning. The language in which the bilingual was dominant at the time of testing was identified using verbal fluency tasks (letter and category fluency) in both English and French.

For the verbal fluency task, participants were given 1 minute to list as many words as possible that start with a specific letter (for letter fluency) or exemplars of the category (for category fluency). Participants were tested in both English and French with a total of 3 letters per language (F, A, S in English; P, F, L in French) and 1 category per language (animals in English; fruits in French). Sequential bilinguals completed the verbal fluency task in their L1 first, before proceeding to their L2. Similarly, simultaneous bilinguals started the task in the language in which they felt most comfortable, before finishing the task in their other language. All words listed by participants were noted and counted to generate a relative language dominance score for each participant across both languages. An average score was calculated for each language (across tasks), in order to obtain a more global estimate, and then the average scores in English and French were combined using the following ratio:

$$Relative\ language\ dominance = \frac{average\ number\ of\ words\ per\ letter\ or\ category\ in\ English}{average\ number\ of\ words\ per\ letter\ or\ category\ in\ French}$$

A score of 1 on this measure indicates a bilingual who is equally proficient on this task in both of their languages. Any score larger than 1 indicates an English-dominant bilingual, and any score smaller than 1 indicates a French-dominant bilingual. The majority of participants were English dominant (12 English-dominant vs. 3 French-dominant bilinguals) with an average score of 1.28.

2.2.1 Prosodic Cue Production Task

The prosodic cue production task was used to characterize participants' ability (or lack of ability) to produce native-like prosodic cues in both English and French. Participants were unaware that the task was intended to investigate prosody in particular. Eighty (80) sentence pairs were used as stimuli, with 40 sentence pairs per language. Target word(s) of a sentence pair shared the same phonology and were able to be interpreted as either one bisyllabic word or two monosyllabic words, depending on how they were segmented (e.g. ‘kiwi’ vs. ‘key we’). This design forced participants to make use of prosodic cues in order to differentiate between the segmentation options and therefore also the meaning of the target word(s). Sentence pairs were identical until the target words to control for factors that may indicate which of the target word(s) fit each sentence pair.

For example:

1. If you would like a **kiwi** I will buy one tomorrow.
2. If you would like a **key we** can duplicate one.

3. Le vendeur **d’horloges** vit à l’hôtel.
4. Le vendeur **d’or loge** à l’hôtel.

Notably, the sentences were not presented in pairs so as to avoid drawing overt attention to the phonological similarity between target words. Instead, stimuli were divided into 4 blocks (2 per language), where the 2 sentences of a pair were never presented in the same block. There were an equal number of sentences of each type (i.e. with one bisyllabic target word vs. two monosyllabic target words) in each stimuli block, and the order of sentences within each block was randomized. However, once the order within a block was established it remained constant for all participants. Sequential bilinguals began the tasks in their L1, while simultaneous bilinguals began the tasks in the language in which they felt the most comfortable.

During the prosodic cue production task, stimuli were displayed individually on a computer screen and participants were asked to read the sentences aloud as they appeared. Responses were recorded using a Marantz PMD-670 digital recorder. Using these recordings, F_0 and duration prosodic cue values were then extracted and used to place participants on a continuum from native-like to non-native-like in both English and French. These prosodic cue production values were then used as the behavioural measure for the production analyses. F_0 (Hz) and duration (ms) production values for both syllables of each target word(s) were identified from the audio recordings using Praat (version 5.4.19, Boersma, 2001). The duration of the first syllable of the target word(s) was measured from the onset of the first syllable of the target word(s) to the offset of the first syllable, and duration of the second syllable of the target word(s) was measured from the offset of the first syllable to the offset of the second syllable. Following this syllable segmentation, mean F_0 values were extracted for each individual syllable using the Pitch function in Praat. In order to compare the F_0 and duration values across sentence pairs, the following calculation was used:

$$prosodic\ cue\ production\ measure =$$

$$\frac{2nd\ syllable\ of\ the\ 1\ bisyllable\ target\ word}{1st\ syllable\ of\ the\ 1\ bisyllable\ target\ word} - \frac{2nd\ syllable\ of\ the\ 2\ monosyllabic\ target\ \ words}{1st\ syllable\ of\ the\ 2\ monosyllabic\ target\ words}$$

The above calculation was generated to compare across target words of a pair (Gilbert et al., 2017; 2019). Similar relative prosodic production measures have also been used previously by Kim (2019). The above calculation was used for both F_0 and duration, although the cues were calculated separately. For example, with the following sentence pair:

1. If you would like a **kiwi** I will buy one tomorrow.
2. If you would like a **key we** can duplicate one.

the duration production measure was calculated as follows:

$$duration\ production\ measure\ = \frac{duration\ of\ "wi"}{duration\ of\ "ki"} - \frac{duration\ of\ "we"}{duration\ of\ "key"}$$

Given that participants were tested in both English and French, this generated four prosodic production measures per participant, one for each prosodic cue (F_0 and duration) in each language (English and French). The above calculation was purposefully designed to compare prosodic cue production of target words by each participant across sentence pairs, rather than directly comparing the raw production scores of the target words across participants. As such, the calculation accounts for individual differences in speech rate and fundamental frequency.

Once F_0 and duration values were calculated, they were used to quantify the degree of native-like prosodic production attained by participants and to place participants on a continuum from native-like to non-native-like in both English and French. This continuum was generated using both the characteristics of native English and French speakers identified in the literature, described above, and from previous work with a larger sample that included both English-dominant and French-dominant bilinguals (Gilbert et al., 2017; 2019). Notably, there was no correlation between native-like attainment of prosodic cue production within or across languages, suggesting that mastery of prosody occurs independently across cues and languages (see Appendix Figures 21 - 24 for further detail).

2.3 Neuroimaging

Participants completed two MRI scans: one for structural analysis (MRI) and one for functional connectivity analyses (rs-fMRI). Data were acquired on a 3T TrioTim Siemens scanner using a 32-channel head coil at the Montreal Neurological Institute. Resting scan images were obtained in 38 3.5mm thick transverse slices, covering the entire brain (TR=2260ms, TE=30ms, matrix size=64×64, FoV=224mm, flip angle = 90°); 132 volumes were obtained in 5:04 min. T1-weighted images were obtained from a 3D magnetization prepared rapid acquisition gradient echo sequence (slice thickness = 1 mm, TR = 2300 ms, TE = 2.98 ms, matrix size = 256 × 256, FoV = 256 mm, flip angle = 9°, interleaved excitation) for both resting state and anatomical scans. Both the resting state and the anatomical scans were acquired as part of a larger study on bilingualism, with participants completing other tasks both in and outside of the scanner. Given this, the same resting state data acquisition parameters reported here were also previously described by Kousaie et al. (2017). The anatomical and resting state scans occurred first and second respectively in task sequence. During the resting-state scan, participants were asked to remain still, to clear their minds and to fixate on a cross that was presented in the center of the screen.

2.3.1 Structural Magnetic Resonance Imaging

Whole-brain voxel-based morphometry (VBM) analyses were performed using SPM12 (Wellcome Department of Imaging Neuroscience, London, UK) with CAT12 toolbox. Standard preprocessing steps were applied. These VBM analyses were then correlated with the prosodic production data to examine potential associations between brain structure in terms of gray matter volume (GMV) and performance on the prosodic production tasks.

2.3.2 Resting State Functional Magnetic Resonance Imaging

The functional connectivity analyses were performed using the custom software CONN (Chai, Castanon, Ongur, & Whitfield- Gabrieli, 2012; Whitfield-Gabrieli & Nieto-Castanon, 2012). Seed-to-voxel correlations were performed using seeds chosen both from the literature and from the regions found to have been associated with significant differences in GMV from prior structural (VBM) analyses. For seeds based on the structural results, the peak of the cluster found during VBM analyses served as the center point for the 6mm sphere seed. For regions from the literature, the Harvard-Oxford atlas was used as a reference for seeded regions beyond the cortex, while cortical regions (IFG pars opercularis and triangularis) were designated following more recent anatomical references (Petrides, 2019; Sprung-Much & Petrides, 2018; 2019)

Results

3.1 Behavioural analyses

3.1.1 Participants' Self-reported Language Proficiency

Self-reported language proficiency was measured in the HLHQ, with mean values noted in Table 2 below. All ability scores were recorded out of a maximum of 7, with participants reporting strong reading, speaking and listening ability in both English (L1) and French (L2). Notably, participants reported on average a majority of conversations (67.35%) in English.

Table 2: Self-Reported Language Assessment (taken from the HLHQ). Reported scores are means.

	English	French
Reading Ability[1]	6.66	6.07
Speaking Ability[1]	6.66	5.87
Listening Ability[1]	6.80	6.20
Percent daily use in conversation	67.35%	32.65%

[1] Out of a maximum score of 7, where 1indicates poor ability while 7 indicates strong ability

3.2 Neuroimaging analyses

3.2.1 Structural analyses

VBM analyses were performed using SPM12 with CAT12 toolbox to relate participants' F_0 and duration production values to GMV across the brain. A threshold of $p(\text{uncorrected})<0.005$, $p(\text{FDR})<0.05$ was applied. A dissociation was found where native-like production of F_0 was associated with GMV in subcortical regions, whereas native-like production of duration was associated with GMV in the cerebellum. In English, more native-like production of F_0 was associated with greater GMV in the bilateral putamen (Figure 1). On the other hand, native-like production of F_0 in French was associated with smaller GMV in the bilateral caudate and the left hippocampus (Figures 2 & 3).

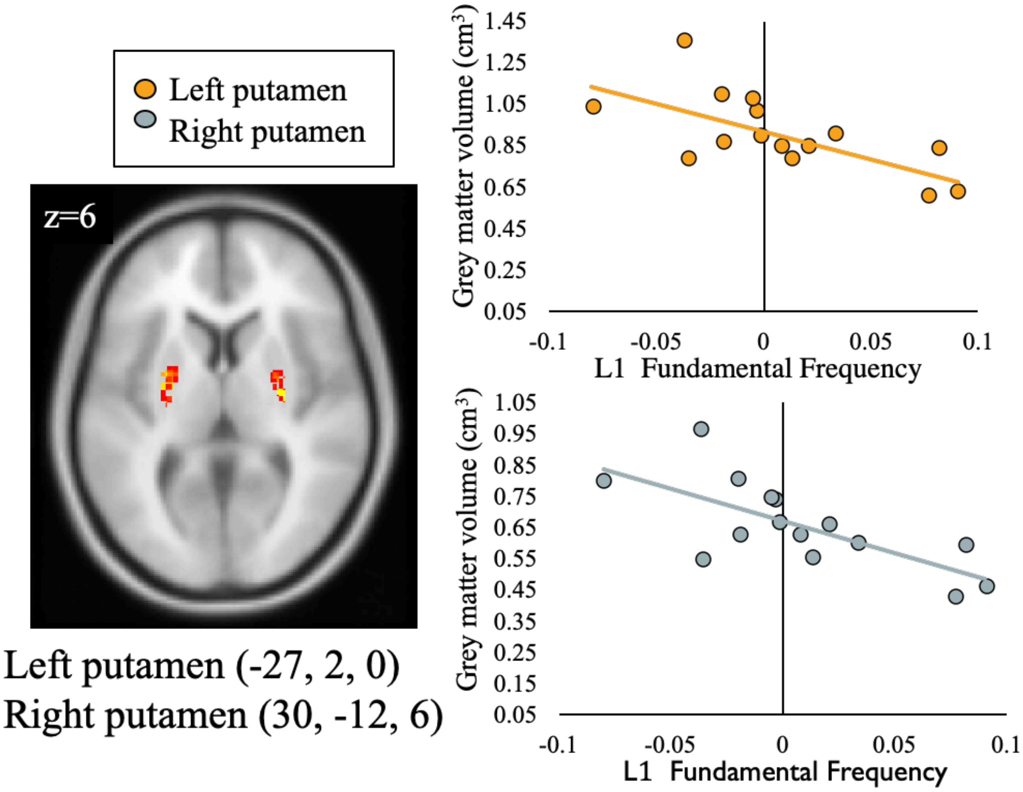


Figure 1: Results from Voxel-Based Morphometry analysis, where native-like production of fundamental frequency (F_0) in English (L1) was associated with greater gray matter volume (GMV) in the bilateral putamen.

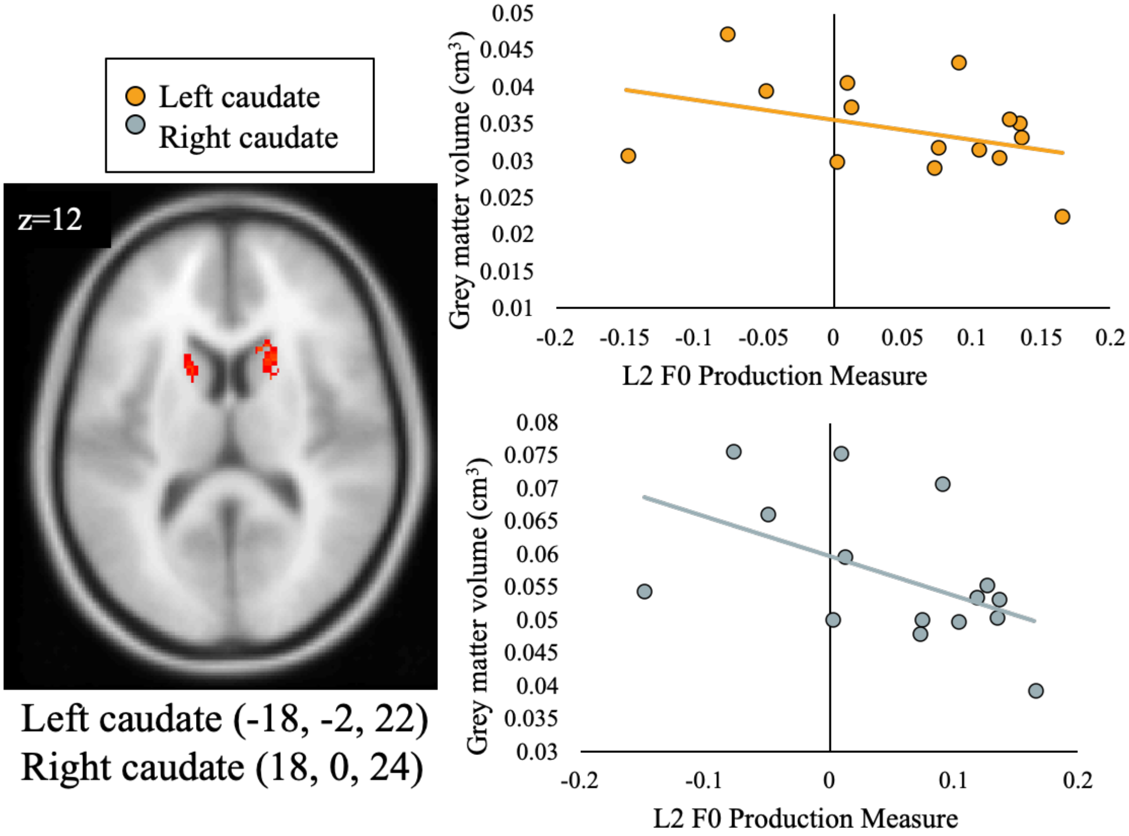
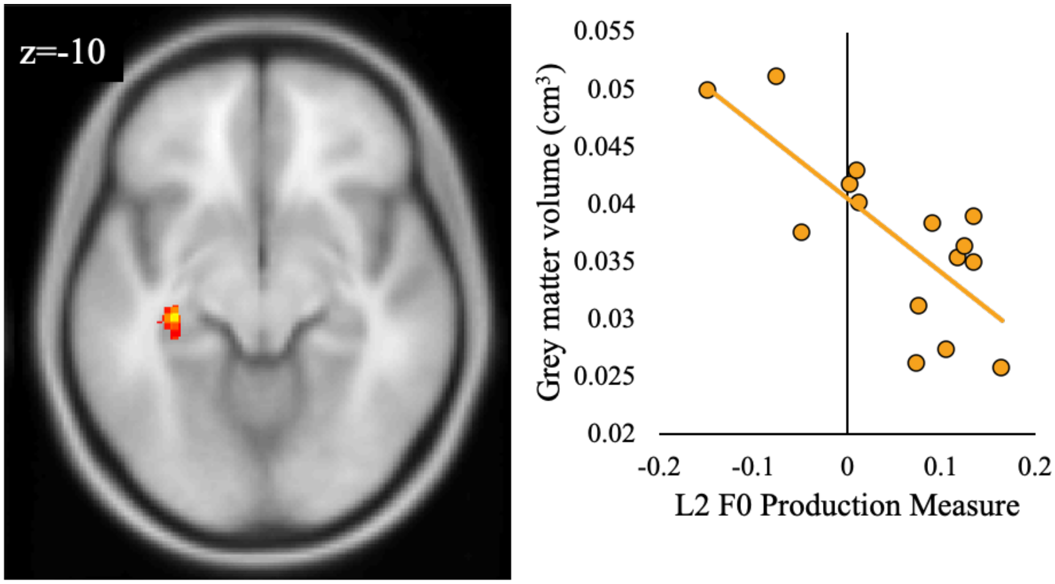


Figure 2: Results from Voxel-Based Morphometry analysis, where native-like production of fundamental frequency (F_0) in French (L2) was associated with smaller gray matter volume (GMV) in the bilateral caudate.



Left hippocampus (-34, -15, -20)

Figure 3: Results from Voxel-Based Morphometry analysis, where native-like production of fundamental frequency (F_0) in French (L2) was associated with smaller gray matter volume (GMV) in the left hippocampus.

In contrast, native-like production of duration was associated with GMV in the left cerebellum in both languages. In English, native-like production of duration was associated with greater GMV in the left cerebellum (Figure 4), whereas in French it was associated with smaller GMV in the left cerebellum (Figure 5). For a full summary of all contrasts, see Table 3 below.

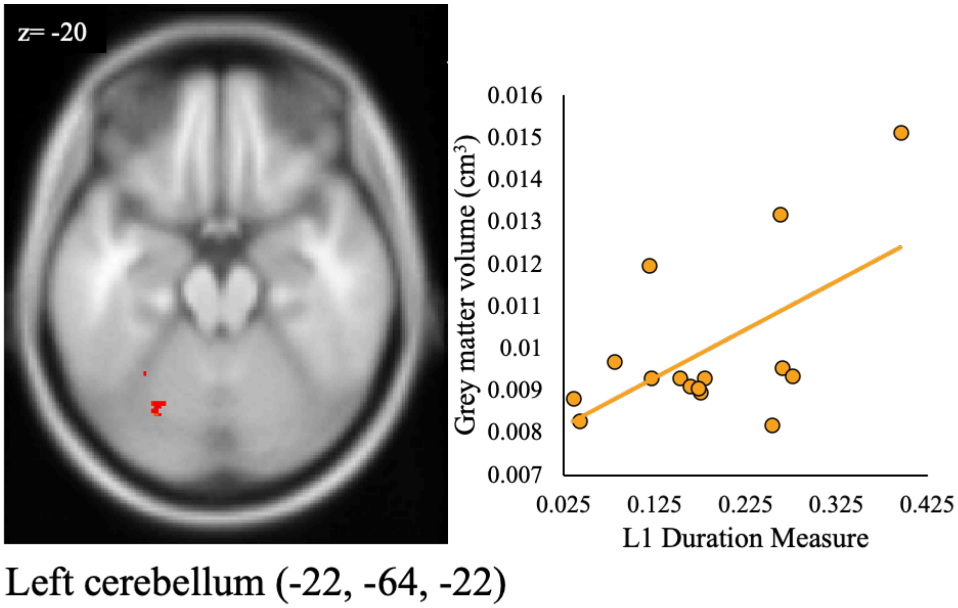


Figure 4: Results from Voxel-Based Morphometry analysis, where native-like production of duration in English (L1) was associated with greater gray matter volume (GMV) in the left cerebellum.

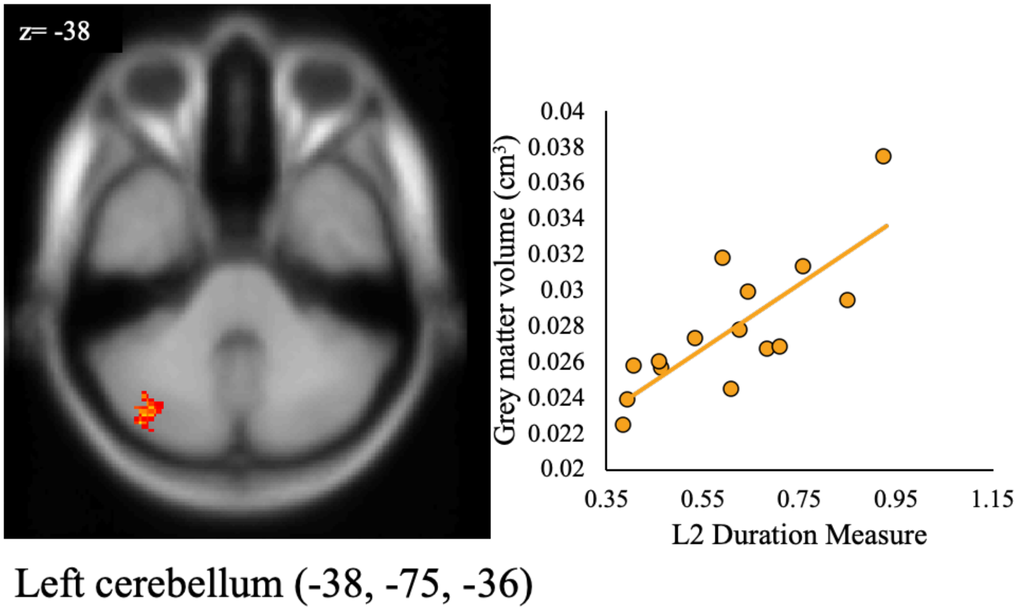


Figure 5: Results from Voxel-Based Morphometry analysis, where native-like production of duration in French (L2) was associated with smaller gray matter volume (GMV) in the left cerebellum.

Table 3: Summary of regions observed to have significant differences in gray matter volume associated with native-like production of F_0 and duration prosodic cues in both English and French from whole-brain voxel-brain-morphometry analyses.

Behavioural measure	**Brain region**	**x, y, z coordinates (MNI space)**	**T value**	**Cluster size (number of voxels)**
F_0 production in English	Left putamen	-27, 2, 0	6.55	331
F_0 production in English	Right putamen	30, -12, 6	6.51	241
F_0 production in French	Left caudate	-18, -2, 22	4.51	171
F_0 production in French	Right caudate	18, 0, 24	6.73	369
F_0 production in French	Left hippocampus	-34, -15, -20	6.18	232
Duration production in English	Left cerebellum	-22, -64, -22	5.26	54
Duration production in French	Left cerebellum	-38, -75, -36	5.63	152

3.2.2 Functional Connectivity Analyses

Functional connectivity analyses were performed using the custom software CONN (Whitfield-Gabrieli & Nieto-Castanon, 2012). For this, we expected native-like prosodic production to be associated with increased connectivity between the basal ganglia (left putamen), the cerebellum (right lobule IV-VII, Crus I) and classical cortical language regions (the left IFG pars triangularis and opercularis), with greater involvement in the second language due to articulatory demands.

3.2.2.1 F_0 Production in English (L1)

The F_0 production in English condition had the highest number of significant contrasts observed. All reported contrasts retained significance ($p<0.05$) following a Benjamini-Holmes correction for multiple comparisons of seeds as well as a False Discovery Rate (FDR) correction for multiple comparisons at the whole brain level. The left putamen seed (taken from significant VBM findings) was found to have three regions for which significant functional connectivity was observed to be associated with native-like production of F_0 in English. First, native-like production of F_0 in English was associated with significantly greater functional connectivity between the left putamen and the left superior frontal gyrus (SFG; Figure 6), with T = 9.28, p = 0.000, k = 201 voxels.

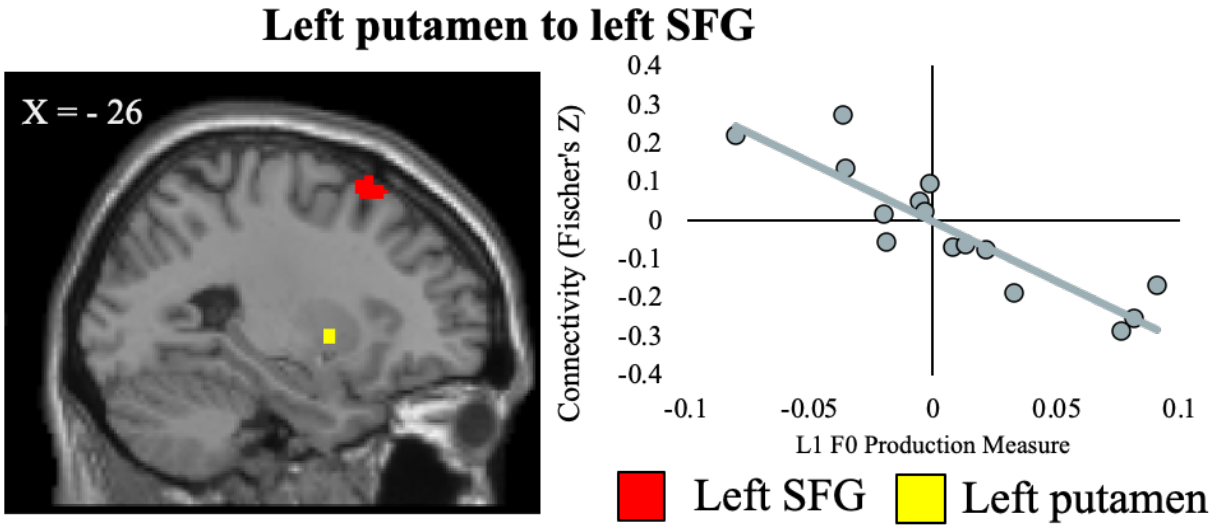


Figure 6: Native-like production of F_0 in English was associated with greater functional connectivity between the left putamen (seed, highlighted in yellow) and the left superior frontal gyrus (cluster, highlighted in red).

Secondly, native-like production of F_0 in English was significantly associated with greater functional connectivity between the left putamen and the right inferior frontal gyrus (IFG, Figure 7) with T = 8.29, p = 0.0315, k = 82 voxels.

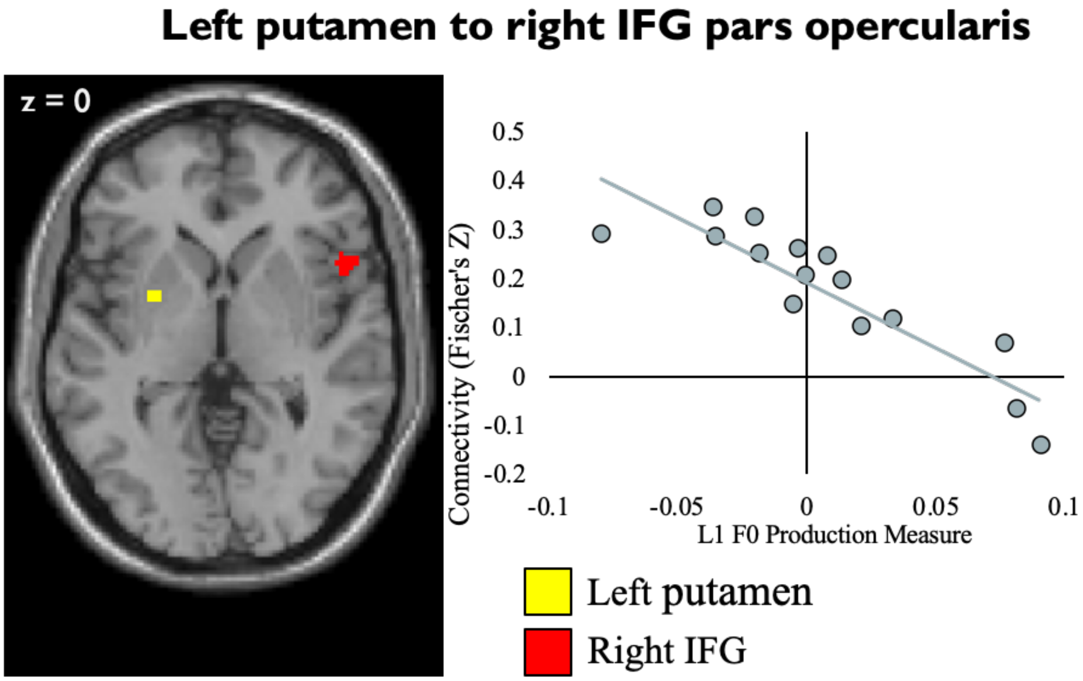


Figure 7: Native-like production of F_0 in English was associated with greater functional connectivity between the left putamen (seed, highlighted in yellow) and the right inferior frontal gyrus pars opercularis (cluster, highlighted in red).

Thirdly, native-like production of F_0 in English was significantly associated with greater functional connectivity between the left putamen and the left anterior and posterior supramarginal gyrus (a/pSMG, Figure 8) with T = 5.25, p = 0.048, k = 73 voxels.

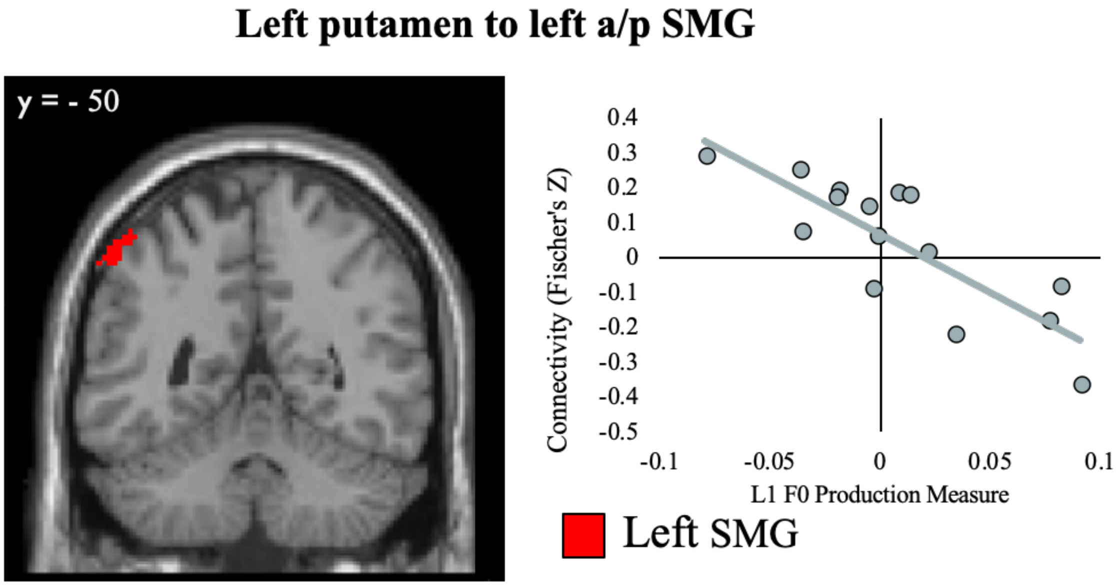


Figure 8: Native-like production of F_0 in English was associated with greater functional connectivity between the left putamen (seed, not visible here, but highlighted in yellow in Figures 5 & 6 above) and the left anterior and posterior supramarginal gyrus (cluster, highlighted in red).

Furthermore, there were multiple findings of greater functional connectivity between the cerebellum and the cortex, specifically the angular and supramarginal gyri associated with native-like production of F_0 in English. Interestingly, these findings extended beyond the cerebellum Crus I-II that was observed in the VBM results, to cerebellum lobule IV/V. The first of these cerebellar connectivity results is the finding that native-like production of English F_0 was associated with greater functional connectivity between the right cerebellum Crus I and the right angular and supramarginal gyri (Figure 9), with $T = 5.35$, $p = 0.000$, $k = 191$ voxels.

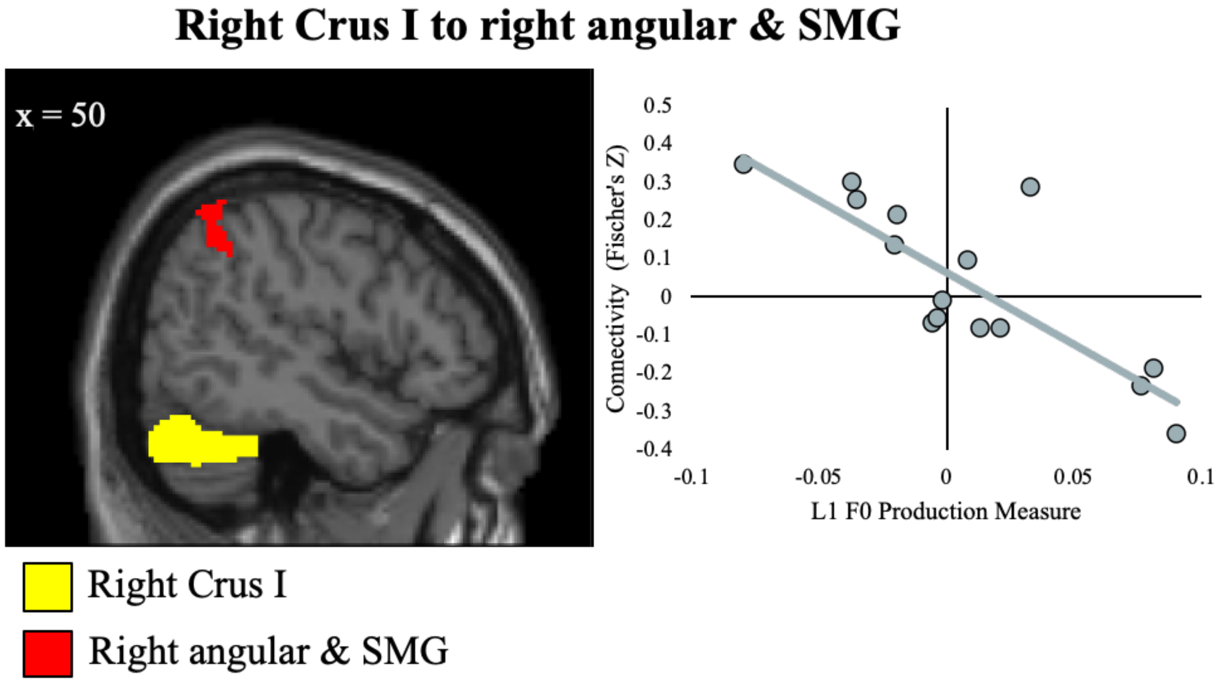


Figure 9: Native-like production of F_0 in English was associated with greater functional connectivity between the right cerebellum Crus I (seed, highlighted in yellow) and the right angular and supramarginal gyrus (cluster, highlighted in red).

Native-like production of English F_0 was also significantly associated with greater functional connectivity between the right cerebellum Crus II and the bilateral angular and supramarginal gyri (Figure 10). For this there were two clusters; one per hemisphere. The right hemisphere cluster was significant with T = 8.96, p = 0.000 with k = 216 voxels. In the left hemisphere, the angular and supramarginal cluster was significant with T = 6.49, p = 0.003 with k = 137 voxels.

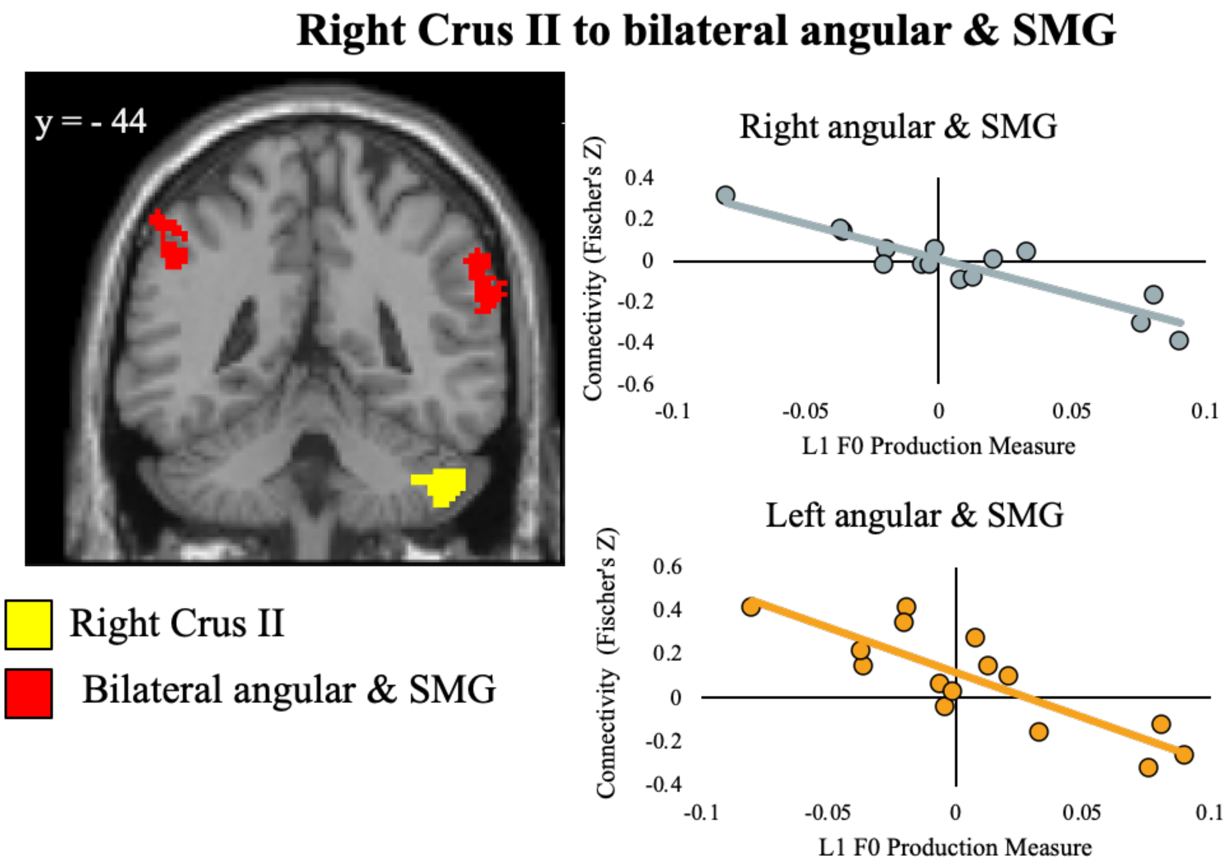


Figure 10: Native-like production of F_0 in English was associated with greater functional connectivity between the right cerebellum Crus II (seed, highlighted in yellow) and the bilateral angular and supramarginal gyrus (cluster, highlighted in red).

Furthermore native-like production of F_0 in English was also associated with significant functional connectivity between the right cerebellum lobule III and the right angular and supramarginal gyri (Figure 11), with $T = 8.62$, $p = 0.000$ with $k = 156$ voxels.

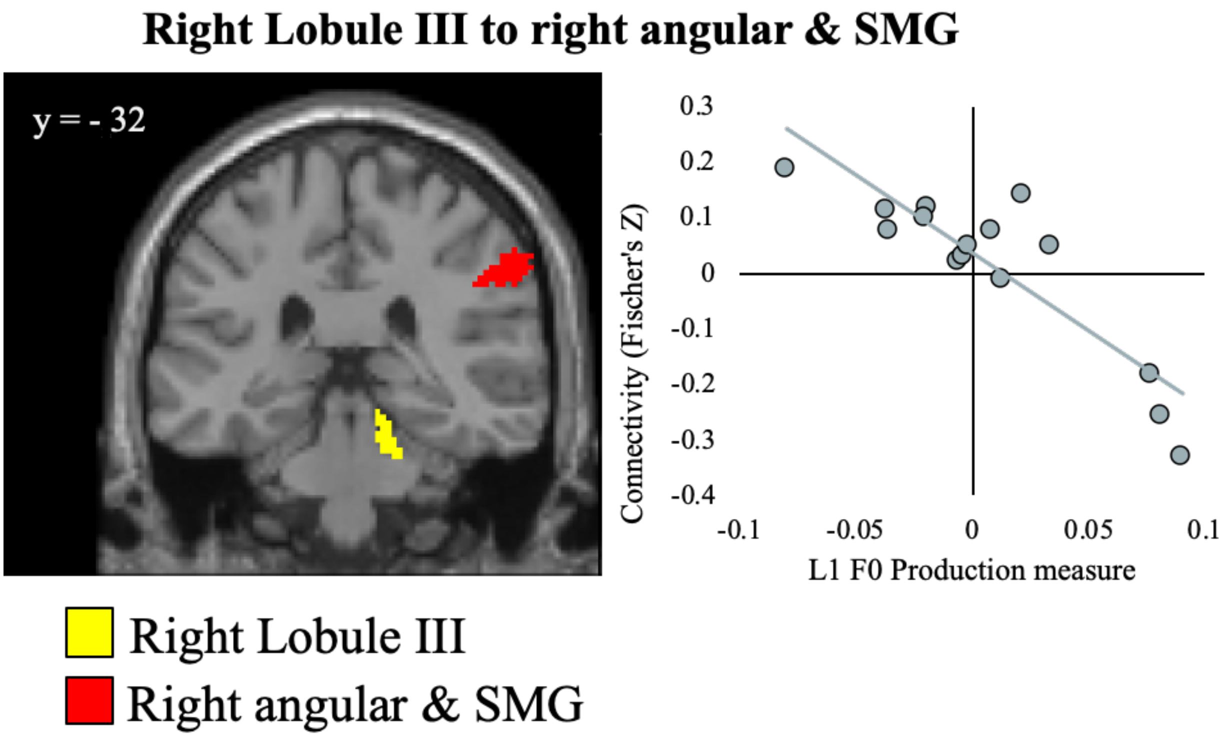
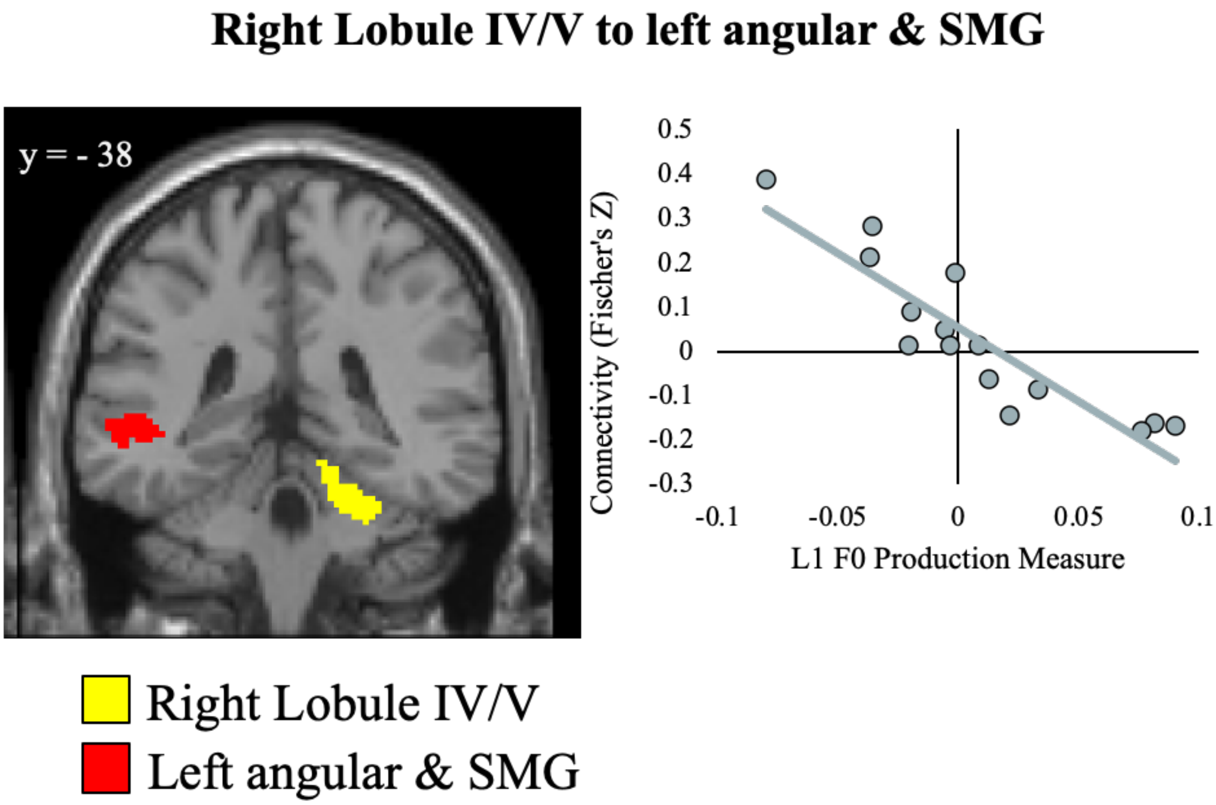


Figure 11: Native-like production of F_0 in English was associated with greater functional connectivity between the right cerebellum lobule III (seed, highlighted in yellow) and the right angular and supramarginal gyrus (cluster, highlighted in red).

Lastly, the native-like production of F_0 in English was significantly associated with increased functional connectivity between the right cerebellum IV-V and the left angular and supramarginal gyri (Figure 12), with T = 8.43, p = 0.000, k = 247 voxels.



Right Lobule IV/V to left angular & SMG

Figure 12: Native-like production of F_0 in English was observed to be associated with greater functional connectivity between the right cerebellum lobule IV-V (seed, highlighted in yellow) and the left angular and supramarginal gyrus (cluster, highlighted in red).

For a full summary of all results from the functional connectivity analyses in associated with F_0 production in English refer to Table 4 below.

Table 4: Summary of all rs-fMRI findings associated with F_0 production in English (L1). All findings retained significance following both a False Discovery Rate (FDR) correction for multiple comparisons for the whole brain comparisons, and a Benjamini-Holms correction for multiple comparisons for regions seeded.

Seed	**Cluster**	**Cluster x, y, z coordinates (MNI space)**	**T value**	**K cluster size**
Left putamen	Left superior frontal gyrus & middle frontal gyrus	-24 +18 +62	9.28	201
Left putamen	Right inferior frontal gyrus (pars opercularis)	+52 +16 +02	8.29	82
Left putamen	Left anterior/posterior supramarginal gyrus	-54 -50 +56	5.25	73
Right Cerebellum Crus I	Right angular & supramarginal gyrus	+52 -48 +42	5.35	191
Right Cerebellum Crus II	Right angular & supramarginal gyrus	+60 -46 +36	8.96	216
Right Cerebellum Crus II	Left anterior/posterior supramarginal gyrus	-50 -40 +38	6.49	137
Right Cerebellum lobule III	Right angular gyrus & anterior/posterior supramarginal gyrus	+56 -30 +38	8.62	156
Right Cerebellum lobule IV/V	Left angular gyrus & posterior supramarginal gyrus	-56 -50 +18	8.43	247

3.2.2.2 F_0 Production in French (L2)

For production of F_0 in French (L2), there were three findings from the functional connectivity data that retained significance following both FDR and Benjamini-Holms corrections.

The first finding was that native-like production of F_0 in French was associated with increased functional connectivity between the right caudate and the bilateral cerebellum Crus II, with

T = 7.13, p = 0.000, and k = 235 voxels (see Figure 13 below). Notably, this was the only significant functional connectivity that linked the cerebellum to French production (across both F_0 and duration).

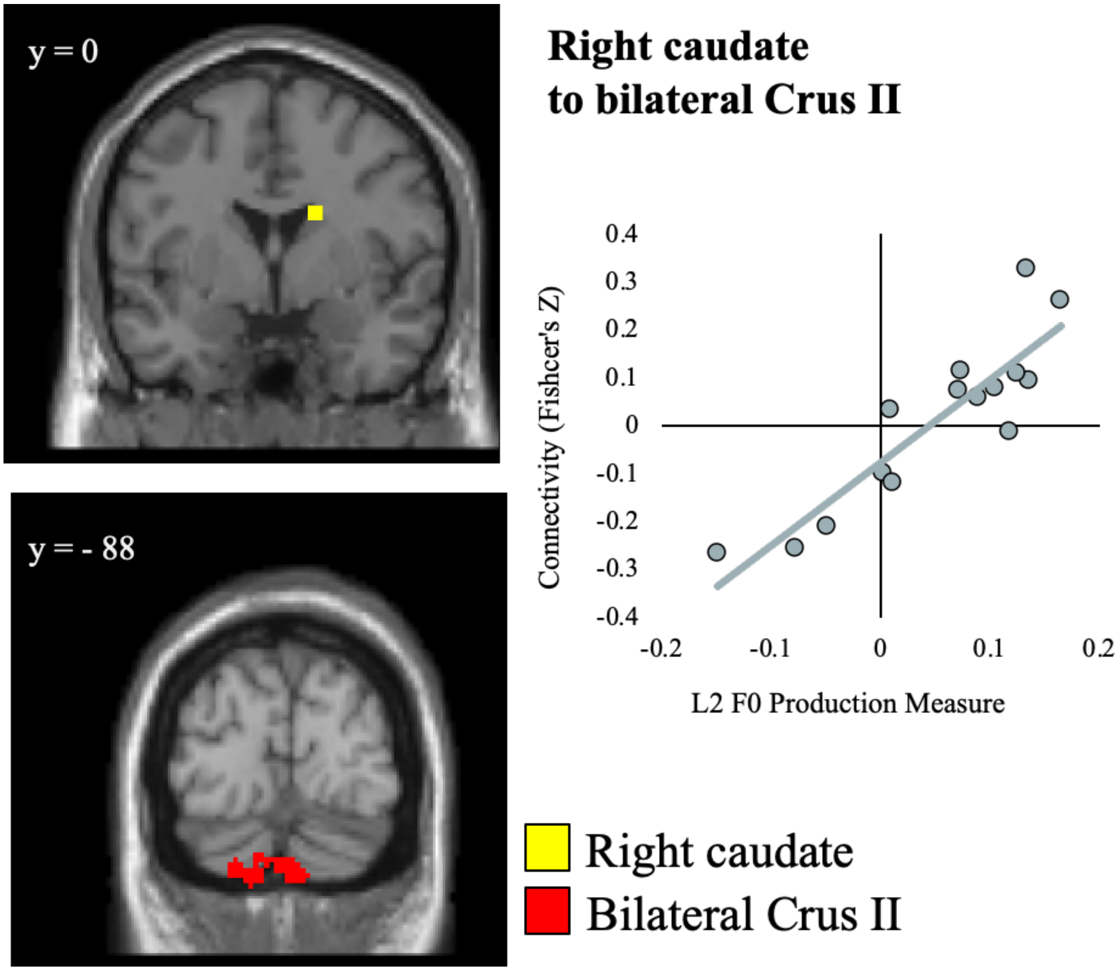
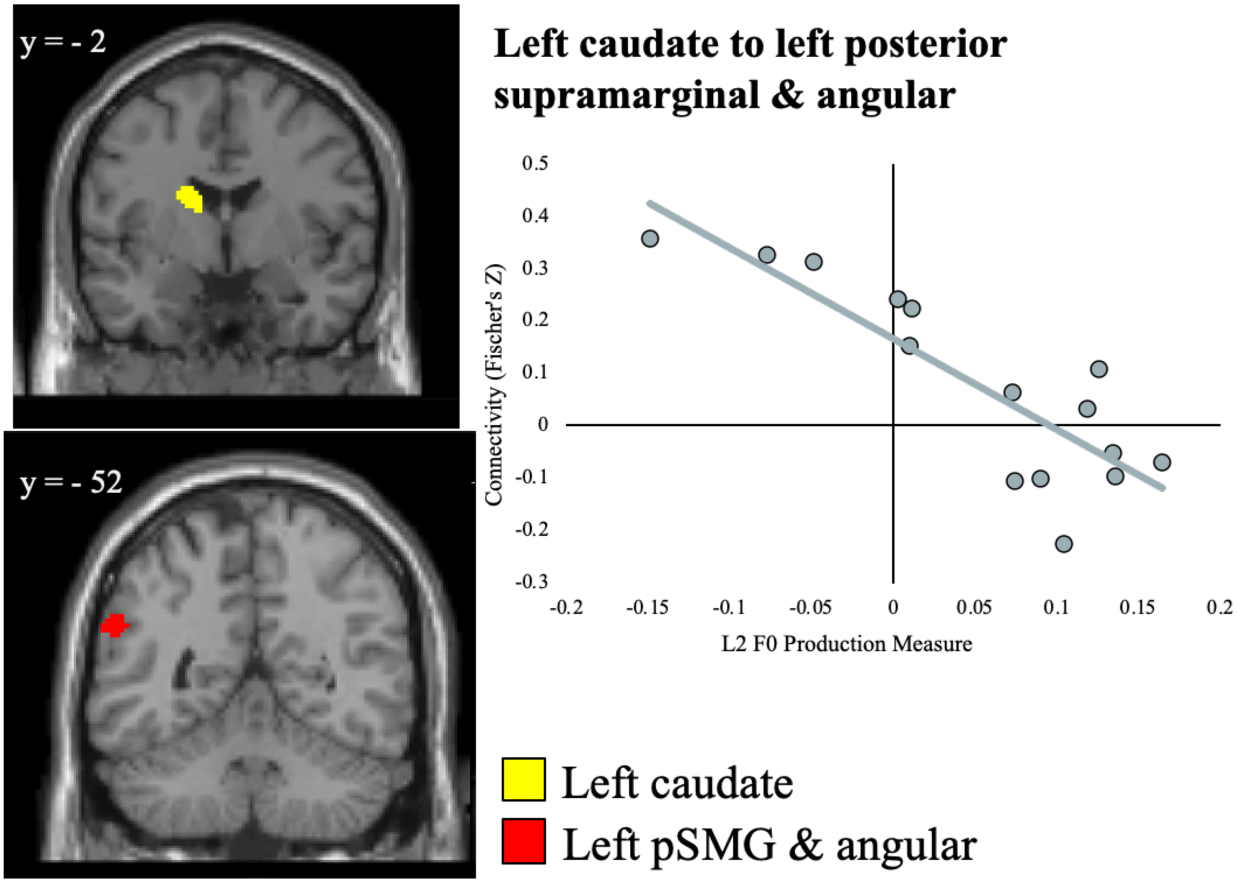


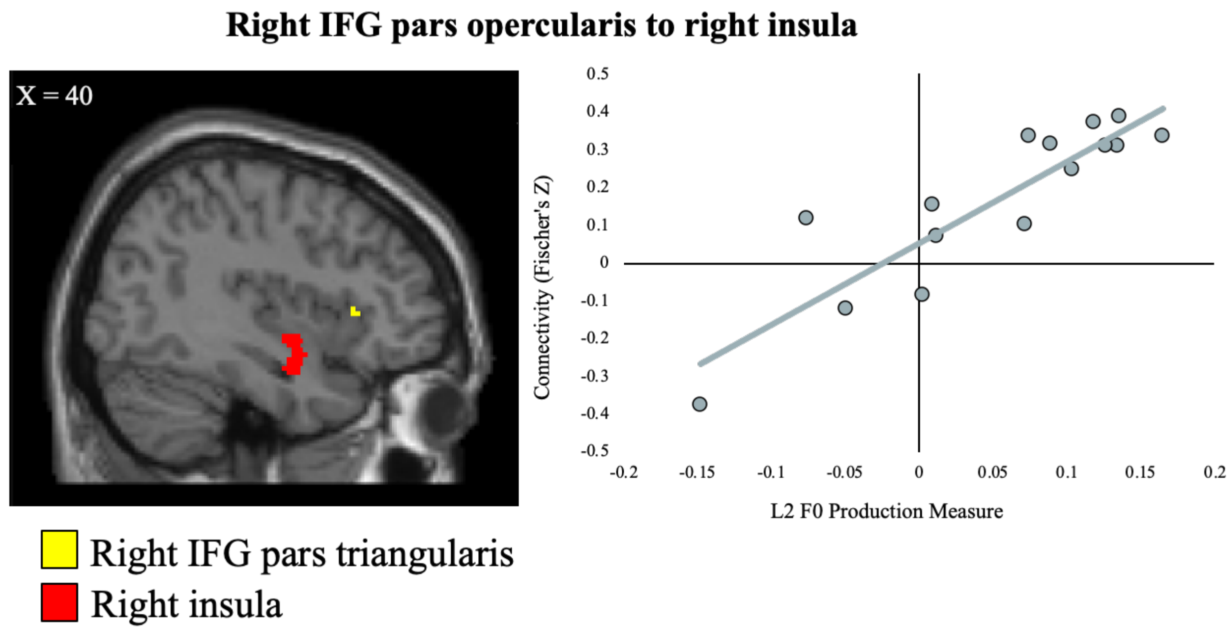
Figure 13: Native-like production of F_0 in French was associated with greater functional connectivity between the right caudate (seed, highlighted in yellow) and the bilateral cerebellum Crus II (cluster, highlighted in red).

Native-like production of F_0 in French was also associated with increased functional connectivity between the left caudate and the left posterior supramarginal and angular gyri (Figure 14), with T = 7.90, p = 0.047 and with k = 87 voxels.



<u>Figure 14:</u> Native-like production of F_0 in French was associated with greater functional connectivity between the left caudate (seed, highlighted in yellow) and the left posterior supramarginal and angular gyri (cluster, highlighted in red).

Lastly, native-like production of F_0 in French was also associated with increased functional connectivity between the right inferior frontal gyrus pars opercularis and the right insula (Figure 15) with T = 5.77 p = 0.006 and k = 137 voxels.



<u>Figure 15:</u> Native-like production of F_0 in French was associated with greater functional connectivity between the right inferior frontal gyrus pars opercularis (seed, highlighted in yellow) and the right insula (cluster, highlighted in red).

For a complete summary of all findings from the functional connectivity analyses associated with native-like F_0 production in French, please refer to Table 5 below.

<u>Table 5:</u> Summary of all rs-fMRI findings associated with F_0 production in French (L2). All findings retained significance following both a False Discovery Rate (FDR) correction for multiple comparisons for the whole brain comparisons, and a Benjamini-Holms correction for multiple comparisons for regions seeded.

Seed	**Cluster**	**Cluster x, y, z coordinates (MNI space)**	**T value**	**K cluster size**
Right caudate	Bilateral Cerebellum Crus II	+2 -86 -40	7.13	235
Left caudate	Left posterior supramarginal & angular gyrus	-56 -52 +28	7.90	87
Right inferior frontal gyrus pars opercularis	Right insula	+50 -06 -08	5.77	137

3.2.2.3 Duration Production in English (L1):

Similarly to the F_0 production in English condition, the results from the duration production in English condition illustrate the connectivity between the cortex, the basal ganglia and the cerebellum. Again, all reported findings retained significance following both FDR and Benjamini-Holms corrections for multiple comparisons. The first finding was that native-like production of duration in English was associated with greater functional connectivity between the right putamen and the right insula (Figure 16), with $T = 6.24$, $p = 0.035$, $k = 85$ voxels.

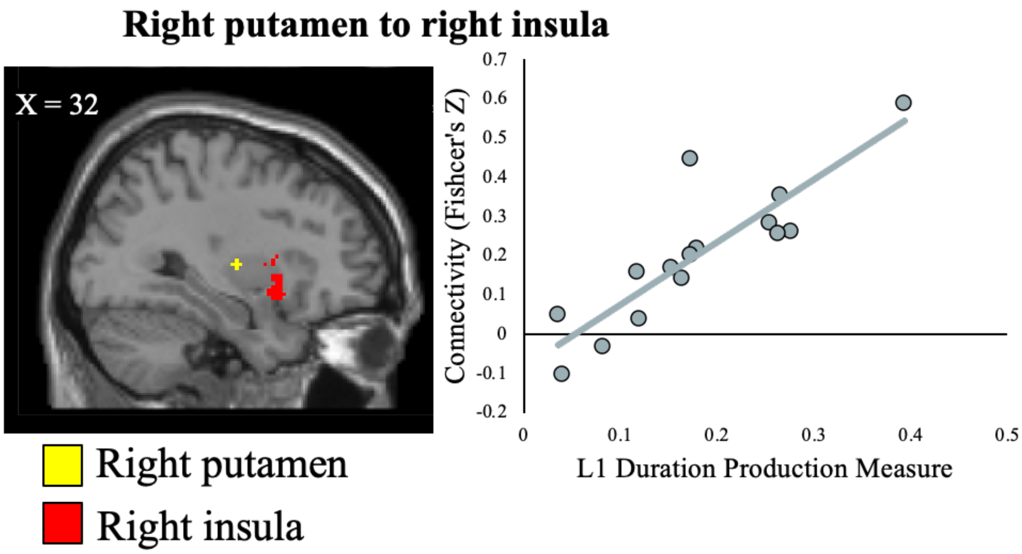

Right putamen to right insula

Figure 16: Native-like production of duration in English was associated with greater functional connectivity between the right putamen (seed, highlighted in yellow) and the right insula (cluster, highlighted in red).

The right caudate was also implicated, with more native-like production of duration in English being associated with greater functional connectivity between the right caudate and the left inferior temporal gyrus (ITG; see Figure 17), with $T = 7.47$, $p = 0.043$ with $k = 79$ voxels. Interestingly, the left ITG has been implicated in previous language studies, although for perception rather than production (Booth et al., 2006).

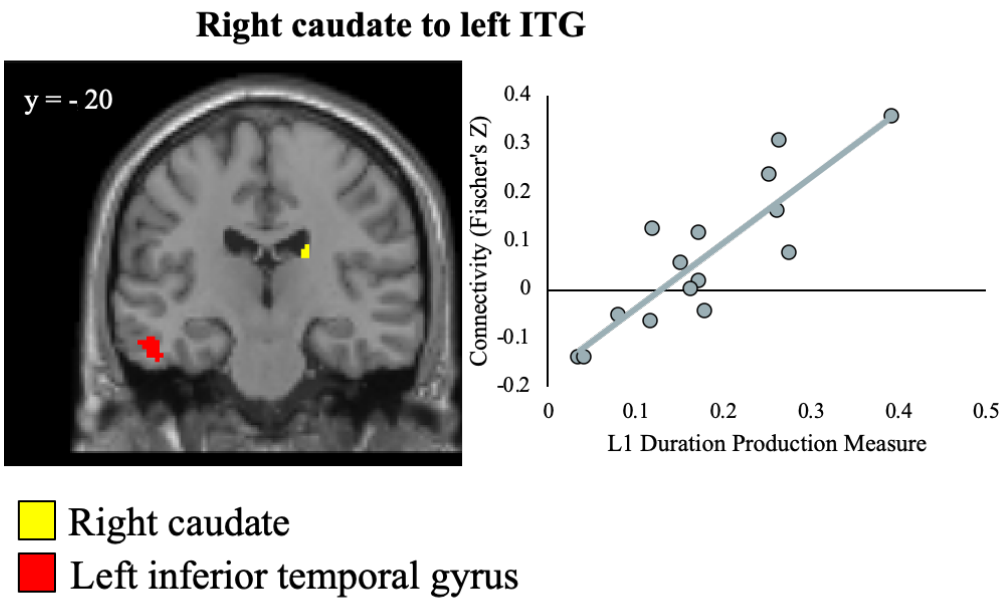


Figure 17: Native-like production of duration in English was observed to be associated with greater functional connectivity between the right caudate nucleus (seed, highlighted in yellow) and the left inferior temporal gyrus (cluster, highlighted in red).

With regard to the cerebellum, native-like production of English duration was associated with increased functional connectivity with the supramarginal and angular gyri. Notably, this follows a similar trend that was also observed in the English F_0 condition. In the case of duration production in English, the left cerebellum Crus II was found to be functionally connected to the right posterior supramarginal and angular gyri (see Figure 18), with T = 9.18, p = 0.000, k = 297 voxels.

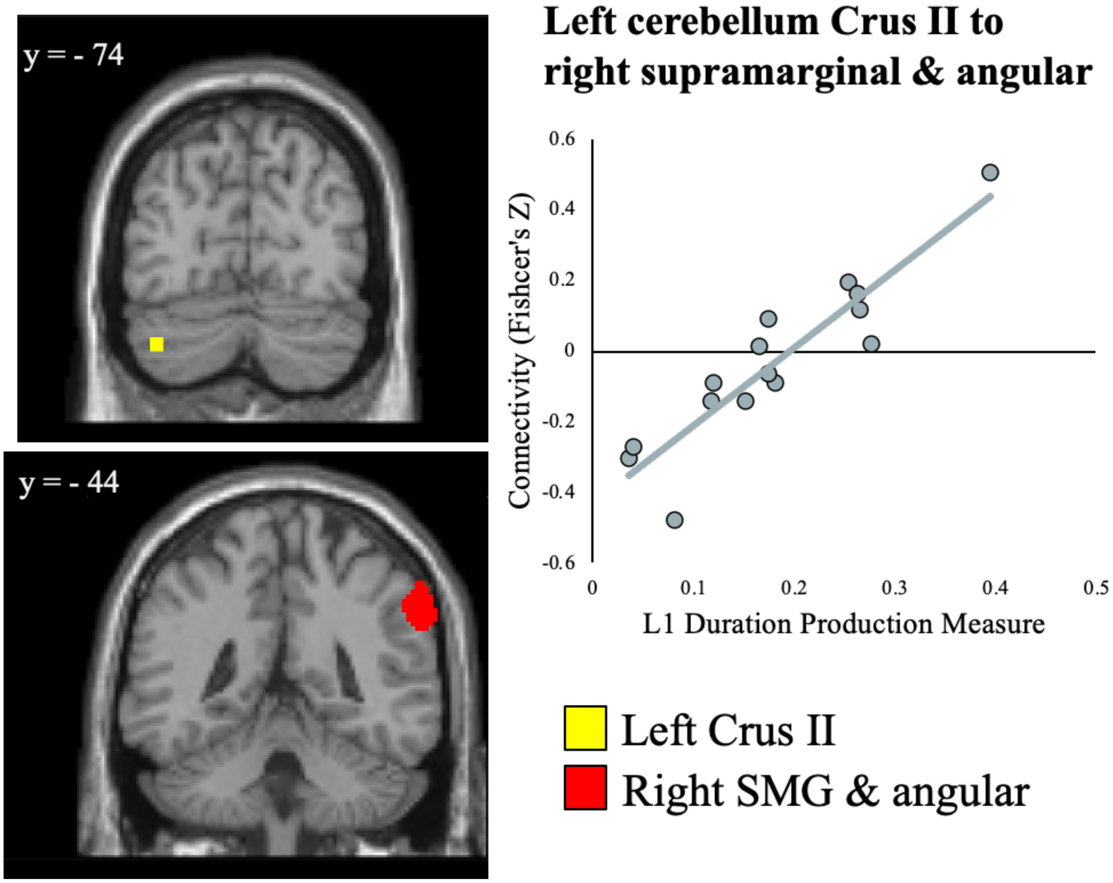


Figure 18: Native-like production of duration in English was observed to be associated with greater functional connectivity between the left cerebellum Crus II (seed, highlighted in yellow) and the right supramarginal and angular gyri (cluster, highlighted in red).

Furthermore, the right cerebellum lobule IV/V was also found to have greater functional connectivity to the right angular and supramarginal gyri associated with more native-like production of duration in English. For this contrast, T = 3.74 p = 0.033 k = 105 voxels, see Figure 19 below for details.

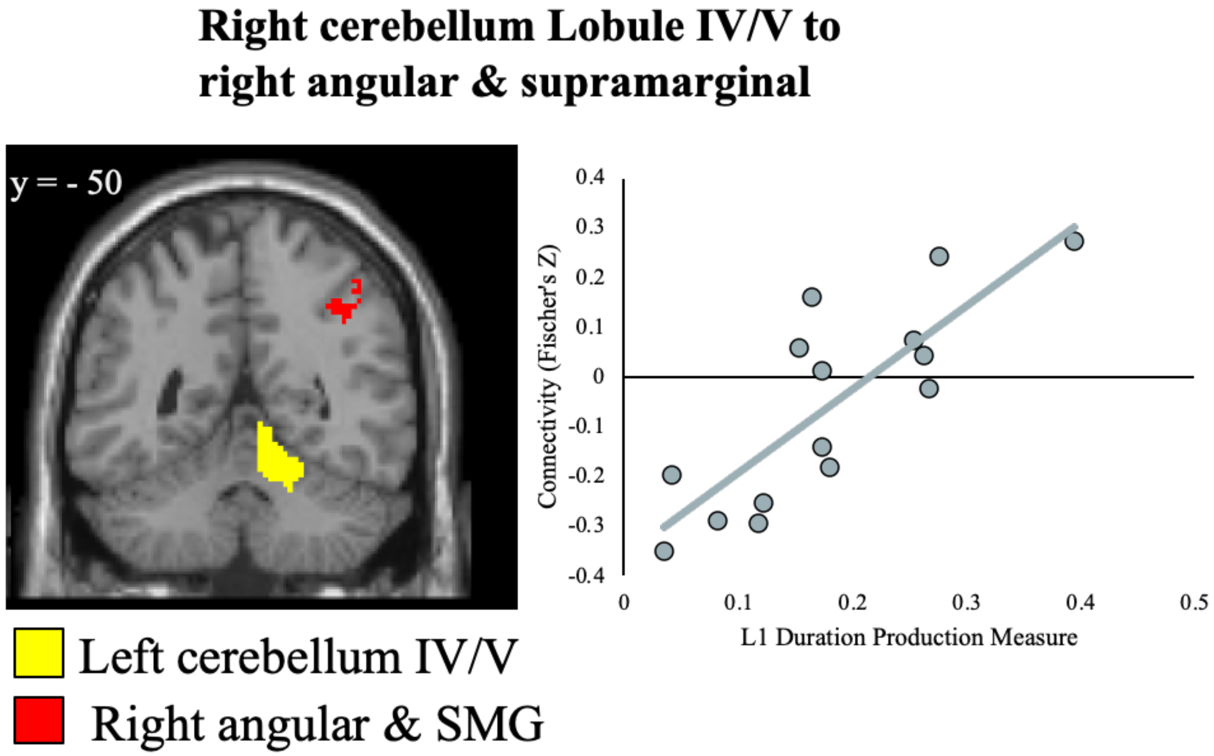


Figure 19: Native-like production of duration in English was observed to be associated with greater functional connectivity between the right cerebellum lobule IV/V (seed, highlighted in yellow) and the right angular and supramarginal gyri (cluster, highlighted in red).

Therefore, the trend of functional connectivity between subregions of the cerebellum and the supramarginal and angular gyri was observed to be associated with native-like production of both duration and F_0 in English. For a summary of all significant functional connectivity findings for the English duration production condition, please refer to Table 6 below.

Table 6: Summary of all rs-fMRI findings associated with duration production in English (L1). All findings retained significance following both a False Discovery Rate (FDR) correction for multiple comparisons for the whole brain comparisons, and a Benjamini-Holms correction for multiple comparisons for regions seeded.

Seed	**Cluster**	**Cluster x, y, z coordinates (MNI space)**	**T value**	**K cluster size**
Right putamen	Right insula	+34 +08 -12	6.24	85
Right caudate	Left inferior temporal gyrus	-52 -20 -24	7.47	79
Left cerebellum Crus II	Right posterior supramarginal & angular gyrus	+66 -44 +36	9.18	297
Right cerebellum lobule IV/V	Right angular, superior parietal lobule & supramarginal gyri	+46 -52 +50	3.74	105

3.2.2.4 Duration Production in French (L2)

There was only one significant functional connectivity finding for the French duration production condition. As can be seen in Figure 20 below, native-like production of duration in French was associated with increased functional connectivity between the left inferior frontal gyrus pars opercularis and the right supramarginal gyrus, with T = 6.42, p = 0.000 with k = 285 voxels. For further detail refer to Table 7 below.

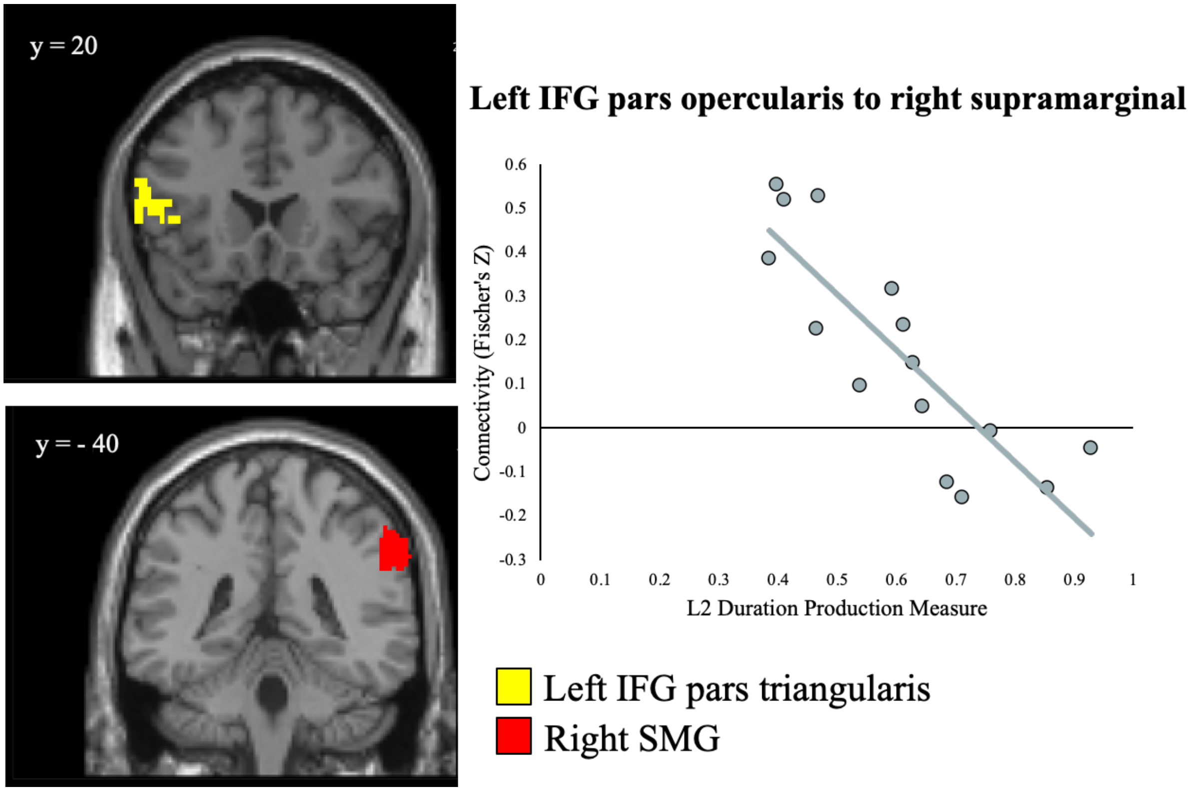


Figure 20: Native-like production of duration in French was observed to be associated with greater functional connectivity between the left inferior frontal gyrus pars opercularis (seed, highlighted in yellow) and the right supramarginal gyrus (cluster, highlighted in red).

Table 7: Summary of all rs-fMRI findings associated with duration production in French (L2). All findings retained significance following both a False Discovery Rate (FDR) correction for multiple comparisons for the whole brain comparisons, and a Benjamini-Holms correction for multiple comparisons for regions seeded.

Seed	**Cluster**	**Cluster x, y, z coordinates (MNI space)**	**T value**	**K cluster size**
Left inferior frontal gyrus pars opercularis	Right posterior and anterior supramarginal gyrus	+64 -40 +38	6.42	285

Discussion

The current study investigated the brain structure and functional connectivity that underlies native-like prosodic attainment in English-French bilinguals. Across both structural and functional connectivity analyses, results from the current project showcase the potential role of the basal ganglia and the cerebellum in linguistic prosody and language production. These findings confirmed our global hypothesis that the basal ganglia and the cerebellum would be implicated in linguistic prosody, although it is notable that the exact subregions that were initially hypothesized were not exactly as observed. With regard to the basal ganglia, we had expected only left putamen involvement due to its link with articulatory control in a second language, but instead observed bilateral putamen as well as caudate involvement in both structural and network-level analyses (Klein et al., 1994; 1996; Abutalebi et al., 2013; Berken et al., 2016).

With regard to the cerebellum, we had hypothesized that the right lobules IV-VI and Crus I would be linked to prosodic production in our task, due to previous work implicating these regions in articulation of speech sounds, and in phonological processing (Marien & Manto, 2016; Vias & Dick, 2017). While we did find cerebellar results, these extended beyond the regions hypothesized, with findings in the left Crus I-II (for VBM) as well as bilateral Crus I-II, and left lobules III-V (for functional connectivity). While the regions of the basal ganglia and the cerebellum discussed above have previously been implicated in language and bilingualism, particularly with the articulatory demands of a second language, few studies have found any link with these regions and prosody specifically (Klein et al., 1994; 1996; Abutalebi et al., 2013; Marien. & Manto, 2016). Therefore, our findings are noteworthy in this regard in highlighting the link between linguistic prosody and the basal ganglia and cerebellum.

4.1 Significance and Implications of the Voxel-Based Morphometry Findings

Findings from the structural analyses closely mimicked expectations from the first hypothesis, that bilinguals with more native-like prosodic production in their languages would show greater GMV in the cerebellum (right lobule IV-VII, Crus I) and basal ganglia (left putamen). The results from VBM analyses demonstrate a dissociation between the prosodic cues, with F_0 mastery being reflected in subcortical regions (i.e. bilateral putamen in English and bilateral caudate and left hippocampus in French) and duration reflected in the left cerebellum. Although the association between F_0 production in French and left hippocampal GMV was unexpected from the literature, interestingly a similar link between the right hippocampus and prosodic word processing has been found previously, albeit for prosodic perception (Heisterueber et al., 2014). Further, the finding of the bilateral caudate being associated with French F_0 production, although unexpected, does follow from previous work implicating the caudate in more executive control and language switching in bilingualism (Zou et al., 2012; Price et al., 1999). Therefore, while the findings highlight the same global regions as were predicted in the hypotheses (namely the basal ganglia and the cerebellum), the specific regions observed to be involved differed somewhat. Notably, the novel findings point toward the possibility that the two prosodic cues may be processed by different regions, as was proposed by Van Lancker & Sidtis (1992), given that the basal ganglia and the hippocampus were implicated in F_0 production while the cerebellum was implicated in duration production, across both languages.

With regard to the specific prosodic cues (i.e. F_0 and duration), the finding of the left cerebellum Crus II being involved in duration production was unexpected from our hypotheses, with regard to both the lateralization and the specific Crus II subregion of the cerebellum involved. Given that previous work had found the cerebellum to be anatomically linked to the contralateral frontal cortex, we had expected the right cerebellum to be involved, due to its expected connection with the left hemisphere IFG (Muller & Meyer, 2014). However, the finding of left cerebellum involvement, suggests that either the right IFG is involved, or that the left IFG is involved functionally, but not through a direct anatomical connection. Further, while the cerebellum Crus II has previously been implicated in language tasks such as verbal fluency, it has not been linked to any prosodic cue in particular (Marien & Manto, 2016). Thus, the current study is novel in implicating the aforementioned subregions of the basal ganglia and cerebellum differentially with each of the prosodic cues investigated.

Another key aspect of this study was the investigation of prosody within the context of bilingualism. In the current study, we had hypothesized that similar brain regions would be implicated across languages for the prosodic production task, but that the greater articulatory demands of the second language (L2; French) would lead to greater basal ganglia and cerebellar involvement, reflected in greater GMV in these regions associated with native-like prosodic cue production. Interestingly, differences in GMV were observed in similar brain regions across languages for the VBM analyses. However, the directionality of the GMV relationship was different across languages, with greater GMV being associated with more native-like production in English while smaller GMV was associated with more native-like production in French. It could be that the combination of greater GMV and smaller GMV in directly adjacent brain regions could be indicative of a more native-like profile overall. However, the cause of this dissociation in directionality is unclear from the current study, and further research is needed to identify whether this is due to the language itself (i.e. French vs. English), the language experience (e.g. L1 vs. L2), some combination of these, or other factors.

4.2 Significance and Implications of the Functional Connectivity Findings

Results from the functional connectivity analyses provide support for a subcortico-cortico-cerebellar network, as was proposed by Heisterueber et al. (2014). Following findings from the current project, this would implicate the putamen and caudate nucleus of the basal ganglia, Crus I – II and lobules III – VI of the cerebellum, and the supramarginal gyrus and the IFG pars opercularis of the cortex. Interestingly, similar subregions of the basal ganglia and the cerebellum were observed across structural and functional connectivity analyses, with the main difference across analyses being the involvement of cerebellar lobules III-VI in the resting state analyses but not in the VBM analyses. Notably, the hippocampus was also not observed to be implicated in any of the functional connectivity results, and accordingly does not appear to play a role in the subcortico-cortico-cerebellar network observed in the current study. Furthermore, the observation of increased functional connectivity between the basal ganglia, cerebellum, the supramarginal and angular gyri was unexpected from the hypotheses. However, this finding does follow from the greater language literature showcasing the role of the inferior parietal lobule (IPL) in speech production and sensorimotor learning. The supramarginal gyrus plays a key role in speech production and has been linked anatomically to the IFG pars opercularis (BA 44), premotor cortex (BA 6) and the cerebellum (Petrides, 2014; Chen & Desmond, 2005; Shum et al., 2011). Notably, the circuit between the cerebellum and the IPL has previously been implicated in the acquisition and mastery of new speech sounds (Chen & Desmond, 2005). This follows from bilingualism research which has linked the inferior parietal lobule with acquisition of a second language (Barbeau et al., 2016). Furthermore, previous work with repetitive transcranial magnetic stimulation (rTMS) has implicated the supramarginal gyrus and the cerebellum in sensorimotor speech articulation learning (Shum et al., 2011). In the study by Shum et al. (2011), participants completed a speech motor adaptation task while undergoing rTMS. Findings suggested that the supramarginal gyrus and the dorsal IPL played a key role in the motor aspects of speech adaptation, specifically monitoring of the discrepancy between the intended and actual speech production, and that these connections with the cerebellum may be involved in this sensorimotor speech learning. Notably, these findings follow from the greater (non-linguistic) motor and movement literature, as the supramarginal and angular gyri have been linked to motor integration and monitoring of discrepancies between intended and actual hand movements (Van Kemenade et al., 2019). Interestingly, even in the case of hand movement, the supramarginal and angular were also shown to have increased functional connectivity to the cerebellum for this motor integration, as was also observed in the rTMS speech study, as well as the current study (Shum et al., 2011; Van Kemenade et al., 2019). Thus, the supramarginal gyrus and the cerebellum have been implicated in various sensorimotor learning aspects of speech production as well as second language learning. Therefore, with regard to language and to speech production more globally, it follows that the functional connectivity observed between the supramarginal gyrus and cerebellum in the current study may be indicative of the sensorimotor adaptation necessary for mastery of prosody across languages. If so, then the supramarginal gyrus may be serving a role monitoring the discrepancy between intended and actual prosodic production during sensorimotor learning of prosodic cues for mastery of both a first and a second language.

Notably, some differences in subregions implicated in functional connectivity analyses were observed across languages. It had been hypothesized that similar brain regions would be implicated across languages for the prosodic production task, but that the greater articulatory demands of the second language (L2; French) would lead to greater basal ganglia and cerebellar involvement, reflected in greater functional connectivity between these regions and the cortex (IFG pars opercularis) associated with native-like prosodic cue production. While the IFG pars opercularis was implicated in functional connectivity analyses, greater supramarginal involvement was observed (as compared to the expected IFG pars opercularis) suggesting that the supramarginal gyrus may be the primary cortical link in this network. The supramarginal gyrus was functionally linked to the cerebellum Crus I-II across both languages, with additional functional connectivity observed in English (L1) between cerebellum Lobules III – VI and the supramarginal gyrus across both prosodic cues, whereas Lobules III-VI were not implicated in French across all analyses. While the prosodic cues are used differently across languages, it remains unclear as to whether this differential use of prosody would lead to differential involvement of the cerebellum and supramarginal gyrus across languages. Interestingly, the cerebellar lobules III-VI have been anatomically linked to the orofacial muscles and are thought to be involved in the articulation of speech sounds (Marien & Manto, 2016; Marien et al., 2014; Vias & Dick, 2017). Given this, it may be possible that the increased functional connectivity between these regions and the supramarginal gyrus associated with native-like production of prosodic cues in English may be a reflection of differing articulatory demands across languages. Since all participants had learned English as their first language, the differing functional connectivity observed across languages may not be specific to the languages themselves (i.e. English vs. French) but rather could be due to the articulatory demands of a second language. Perhaps had native francophone participants been tested rather than native anglophones, then increased functional connectivity might have been observed between the cerebellar lobules III-VI and the supramarginal gyrus. However, this is beyond the scope of the current study, and further work would need to be conducted in order to discern whether this is truly due to a difference in native language (i.e. L1 vs. L2), or whether it is due to the specific language itself (i.e. English vs. French).

4.3 Conclusion

The current study used a novel design that aimed to provide a more complete understanding of the neural networks involved in prosodic production than has been seen in previous literature. Many attributes of the design contribute to this; first, the combined use of rs-fMRI and structural MRI in the current study allows for production analyses with minimal artefacts and for a more nuanced and holistic analysis overall. Likewise, the choice of exclusively bilingual participants allows for comparison across bilinguals to examine the neural underpinnings of prosodic mastery across multiple languages. Furthermore, the use of quantitative measures to measure prosodic cue production eliminates the need for native speakers to serve as raters, a commonly used methodology for determining whether participants perform as native-like or not. With the quantitative method used in the current study, participants' production can not only be more accurately measured, but can also be separated by prosodic cue (i.e. F_0 vs. duration) for neuroimaging analyses.

The brain structure and functional connectivity supporting mastery of prosody across languages was investigated in the current study, and results supported our hypothesis that the basal ganglia and the cerebellum are involved in prosodic production in bilinguals, and that these regions may be working in together with the cortex through a subcortico-cortico-cerebellar network. Further, the current study identified differences in brain structure and functional connectivity associated with native-like prosodic production across languages, observing differing directionality, with greater GMV associated with native-like prosody in English but smaller GMV in French, and recruitment of more cerebellar subregions in English, potentially reflecting differing articulatory demands across languages.

4.4 Future Directions

Future work will be needed to clarify whether the differences observed across languages in the current study were driven by effects due to the native language (L1 vs. L2) or the specific language itself (English vs. French). It would be interesting to determine whether the findings observed in the current study hold true across other language pairs. Moreover, a key limitation of this study is the sample size (n = 15). The current study investigated both simultaneous (n = 9) and sequential (n = 6) bilinguals. Future work will need to examine a larger participant group with a wider range of language experience. With a variety of language experience profiles in the sample, there would be a wider array of levels of mastery of the prosodic cues across languages, providing the potential for a more detailed analysis. Notably, the current study only investigates prosodic production and not perception. It would be interesting to extend the examination of brain structure and functional connectivity supporting prosody to investigate native-like prosodic perception, in order to determine whether there are similarities across mastery of production and perception.

Results from the current study may also shine a light on prosodic impairments observed in conditions associated with brain damage or impairments in the basal ganglia or the cerebellum, such as ataxic dysarthria and Parkinson's disease. The joint integration of the regions observed in the current study in a network for prosodic production may help to explain why lesions across these regions can lead to various prosodic impairments (Jonkers et al., 2017; Marien et al., 2019). This has historically been a key issue highlighted in studies of Foreign Accent Syndrome (FAS), a condition wherein patients develop what is perceived to be a foreign accent following brain damage often due to stroke or injury (Jonkers et al., 2017; Marien et al., 2019). Remarkably, there have been various brain regions linked to FAS, and the basal ganglia and the cerebellum have been implicated in different cases (Jonkers et al., 2017; Marien et al., 2019). It has been hypothesized that the perceived accent characteristic of FAS may be reflective of a prosodic impairment and may be a compensation mechanism due to a mild motor impairment caused by the brain damage (Jonkers et al., 2017). If so, then it may be that damage at various regions across the subcortico-cortico-cerebellar network observed in the current study may be linked to similar prosodic impairments. Potentially if other regions in the network are able to compensate for the damaged region, this could lead to the condition resolving itself, as has been observed in nearly a quarter of FAS cases in a recent review paper (Marien et al., 2019). Naturally, this is beyond the scope of the current study, and future work will be required to shed light on the role of this subcortico-cortico-cerebellar network in patients with impaired prosodic production.

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Appendix

Figure 21: (Lack of) Relationship between mastery of the duration and F_0 prosodic cues in English. The correlation coefficient (r) is 0.133 showing that there is no strong relationship between mastery of duration and F_0 in English.

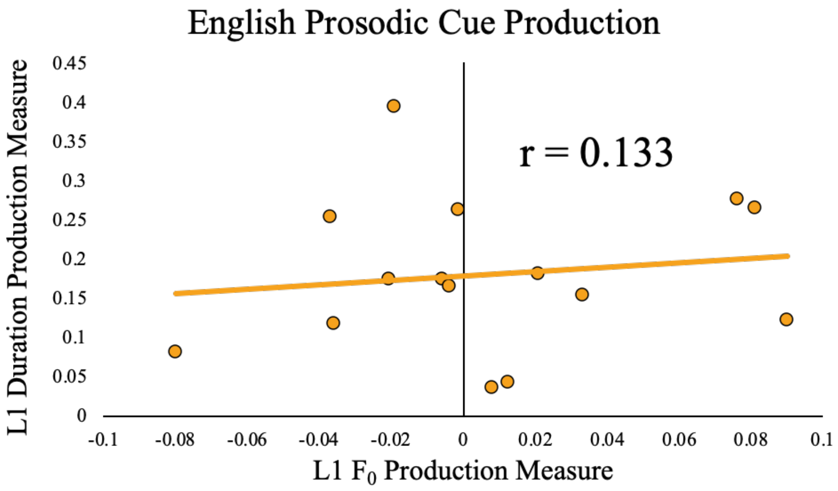


Figure 22: (Lack of) Relationship between mastery of the duration and F_0 prosodic cues in French. The correlation coefficient (r) is 0.087 showing that there is no strong relationship between mastery of duration and F_0 in French.

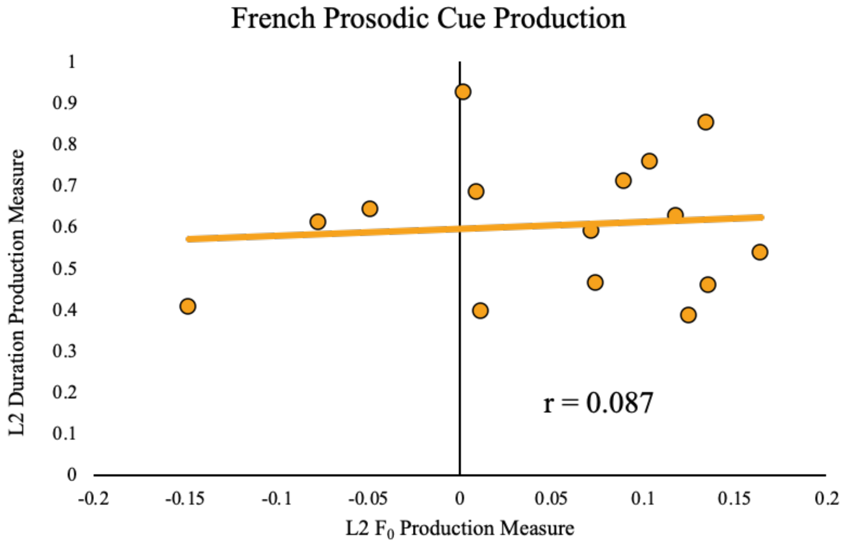


Figure 23: (Lack of) Relationship between mastery of the F_0 prosodic cue in English and French. The correlation coefficient (r) is 0.341 showing that there is no strong relationship between mastery of F_0 across languages.

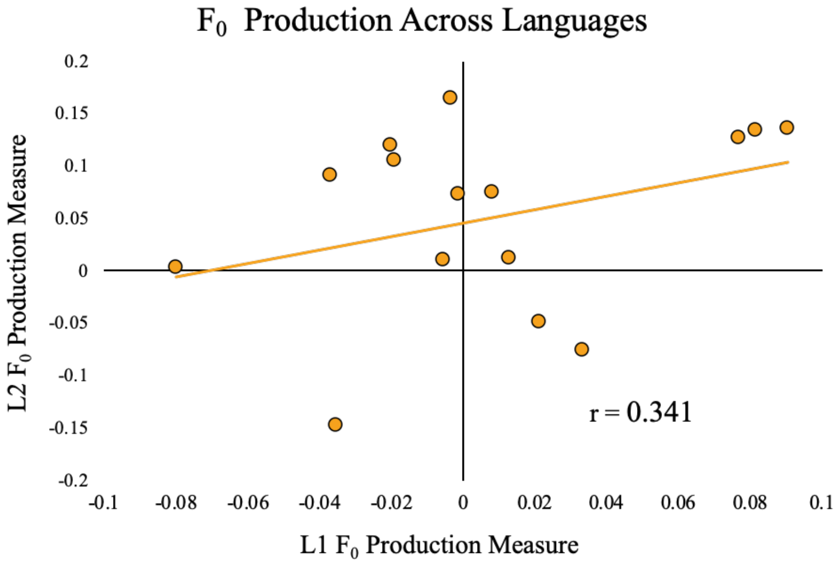
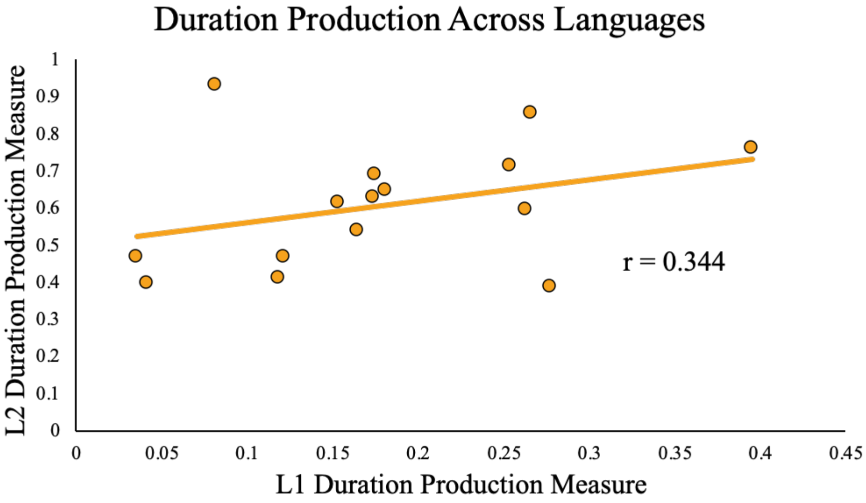


Figure 24: (Lack of) Relationship between mastery of the duration prosodic cue in English and French. The correlation coefficient (r) is 0.344 showing that there is no strong relationship between mastery of duration across languages.



Health and Language History Questionnaire

The purpose of the following questionnaire is to obtain more information about your language and health history for the purpose of matching the groups included in the current study on bilingualism and language learning. If you are uncomfortable answering any of the questions feel free to leave them blank. Thank you!

DATE: _______________________ Participant ID: _____________________

Section 1: Demographic information

3. Date of Birth (day/month/year): 2. Age:
4. Sex:
5. Handedness:
   (Please also complete attached handedness inventory)
6. Education: What is the highest level of education that you have completed? You can include information such as "attended but did not complete"
   Primary school
   High School; where did you completed high school (province, Country)?
   CEGEP
   College/University undergraduate degree (e.g., BA, BSc)
   Graduate degree (e.g., Master's degree)
   Graduate degree (e.g., Ph.D., MD)
   Other; please specify)
7. What is your current marital status?
   Single – never married
   Married / Common-law
   Separated
   Divorced
   Widowed
   Cohabit
8. What is your main occupation?
9. If you are married, what is your spouse's highest level of education and their main occupation?

10. What is your mother's highest level of education and her main occupation (if retired, what was her occupation prior to retirement?)

11. What is your father's highest level of education and his main occupation (if retired, what was his occupation prior to retirement?)

12. Where were you born?

    If not in Canada, how long have you been in Canada?

13. Where were your parents born? (If not in Canada, please indicate if they are currently in Canada, how many years they have been in Canada, their native language and other languages that they speak):

	Country of birth	Years in Canada	Native language	Other languages
Mother				
Father				

13. Do you play a musical instrument?

    If "yes",

    a. Do you have any formal musical training?
    b. Do you still play?
    c. How frequently?
    d. Can you read music?
    e. Do you consider yourself a musician?

<u>Section 2:</u> Language background and experience

1. Do you speak more than one language?

   If you answered "no", skip to the next section

   If you answered "yes", please list the languages that you speak in order of fluency (with the most fluent first):

2. Please rate your current ability on reading, writing, speaking, and listening for all languages you know according to the following scale (circle the number in the table):

1	2	3	4	5	6	7
Very poor	*Poor*	*Fair*	*Functional*	*Good*	*Very good*	*Native-like*

Language	Reading	Writing	Speaking	Listening

3. Have you ever taken a standardized language proficiency test in your non-native language(s) (e.g., TOEFL? If yes, please indicate the name of the test, the languages assesse, and the scores that you received. If you can't remember, please guess. If you remember only the percentile of your score, write it in the place of the score.

Test	Language	Actual Score	Guessed Score

4. Do you have a foreign accent in the languages that you speak? Please rate how strong you think your accent is according to the following scale (circle the number in the table):

1	2	3	4	5	6	7
None	*Little*	*Some*	*Intermediate*	*Strong*	*Very Strong*	*Extremely Strong*

Language	Strength of accent

5. At what age did you first start to learn each language in terms of speaking (at what age did you speak your first words?), reading, and writing, and the number of years you have spent learning each language.

Language	Age first learned the language			Number of years spent learning (cumulative)
	Speaking	Reading	Writing	

6. Please indicate the age at which you started to learn each language in the following situations – indicate the age in the boxes for only situations that are relevant.

Language	At home	At school	After immigrating to the country where spoken	Informal setting (e.g., nannies or friends)	Software (e.g., Rosetta Stone)	Other (please specify: ________)

7. Please indicate the language(s) used by your teachers for general instruction (e.g., history, math, science) at each schooling level. If you switched language within a level please indicate the level and the languages.

   Primary School:

   High School:

   CEGEP:

   College/University:

   Other:

8. Have you ever lived or travelled in another country for more than three months where you were required to speak another language other than your native language(s)? If so, please indicate the country, your length of stay and the year that you visited, the language(s) that you learned or tried to learn, and you frequency of use of the language while visiting the country and currently. Please use the following scale and circle the number in the table:

1	2	3	4	5	6	7
Very poor	*Poor*	*Fair*	*Neutral*	*Good*	*Very good*	*Excellent*

Country	Length (cumulative) and Year of stay	Language	Frequency of use during visit	Frequency of use currently

9. How good do you think you are at learning new languages (e.g., relative to friends or people you know). Circle one:

1	2	3	4	5	6	7
Very poor	*Poor*	*Fair*	*Neutral*	*Good*	*Very good*	*Excellent*

10. At what age do you consider that you became fluent in each language in terms of speaking, reading and writing? Please indicate and age in each box; if you do not consider yourself fluent please indicate “not fluent”.

Language	Age of Fluency		
	Speaking	Reading	Writing

11. Please estimate the total number of hours each day that you spend engaged in the following activities, and indicate what percentage of that time you spend engaged in that activity in each of the languages that you know (please write down the languages). If you are not currently engaged in an activity using that language write “0”; the total percentage for each activity should equal 100%.

Activity	Total hours per day	Language: ____________	Language: ____________	Language: ____________
Listen to radio / watching TV				
Reading for fun				
Reading for work				
Reading on the internet				
Writing emails to friends				
Writing articles / papers				
Other (specify):				

12. Please estimate the percent of conversations that take place in each of your languages, and what percentage of that is with the following people. The total across languages should equal 100% and the total with in each language should equal 100%.

Language	% of total conversations	Family members	Friends	Classmates	Co-workers	

13. How often do you use your languages for the following activities? Use the following scale and circle the number in the table.

1	2	3	4	5	6	7
Never	*Rarely*	*Occasionally*	*Sometimes*	*Frequently*	*Very Frequently*	*Always*

Language	Arithmetic (e.g., count, add, multiply)	Remember numbers (e.g., student ID, telephone)	Dream	Think	Talk to yourself	Express anger or affection

14. What proportion of your current friends are speakers of the languages that you know well? Please indicate the language and the percentage of your total number of friends that speak that language (the total should equal 100%).

Language	Percent of total number of friends

15. In which language (among your two best languages) do you feel you usually do better or feel more comfortable? Indicate the language for each condition.

	At home	At work / At school	At a party or other social context
Speaking			
Writing			
Reading			

16. Do you mix words or sentences from two languages in your own speech (e.g., say a sentence in one language but use a word or phrase from another in the middle of the sentence)? Yes / No

If you answered "no", please move on to the next section.

If you answered "yes", please continue with the following questions

17. a) List the two or more languages that you mix with different people, and estimate the frequency of mixing/switching in normal conversation according to the following scale (circle the number in the table):

1	2	3	4	5	6	7
Never	*Rarely*	*Occasionally*	*Sometimes*	*Frequently*	*Very Frequently*	*Always*

Languages mixed/switched	Relationship	Frequency
	Family members	
	Friends	
	Classmates	
	Co-workers	

17. b) Under what situations from those listed below are you most likely to mix/switch between two languages, and which languages do you mix/switch between? Please list all language combinations that apply to each situation (e.g., English and French; from English to French).

Situation	Mix/Switch between which languages (list all that apply)
When I don't know the word in one language	
A word comes to me faster in one language	
It is difficult for me to control which language I am speaking in	
I switch between languages on purpose	
Other (specify):	

17. c) Please indicate if there are situations in which you are more likely to mix or switch between languages and what those situations are.

17. d) Please indicate if there are situations in which you think that it is inappropriate to mix or switch between languages, and what those situations are.

18. Do you feel that you are bilcultural or multicultural (e.g., growing with parents or relatives from different cultures, or you lived in different cultures for extended periods of time)? Yes / No

If "yes", which culture (and its language) do you identify more strongly with? Use the following examples and scale to indicate the strength of your cultural identification:

1	2	3	4	5	6	7
None	*Very Weak*	*Weak*	*Intermediate*	*Strong*	*Very Strong*	*Extremely Strong*

Culture and its Language	Like its food	Like its music	Like its art	Like its cities and landmarks	Will root for its athletic teams

19. Is there anything else that you think is interesting or important about your language background or language use?

<u>Section 3:</u> Health information

1. Do you have any visual problems (e.g., cataract, colour blindness, wear glasses)?

2. Do you have any hearing problems (e.g., hearing loss, do you wear a hearing aid)?

3. Have you ever had a head injury?
   If "yes",
   What was the cause?
   What was the outcome?

4. Do you have a history of neurological disorder?

5. Have you ever had any major surgery? What for?

6. Do you have any metal prostheses, screws, plates or fragments?

7. Do you have any piercings or tattoos? How many, and where are they located?

8. Do you have any allergies?

9. Are you claustrophobic?

10. Are you pregnant?

11. Have you ever had an MRI before? For what?

12. Do you currently take any medications?

    If "yes", please list the medications and indicate what condition you are taking them for and how long you have been taking them for

Medication	Reason for consumption	Duration of consumption

13. Do you drink alcohol?

    If "yes", approximately how many drink of alcohol do you have per week?

14. Do you use non-prescription drugs for recreational purposes? If "yes", which ones and how many times per week?

Drug	Frequency of use (per week)

Edinburgh Handedness Inventory

DATE: _______________________ Participant ID: _____________________

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put ++*. If any case where you are truly indifferent put + in both columns.

Some of the activities require both hands. In these cases, the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all with the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
i. Which foot do you prefer to kick with?		
ii. Which eye do you use when using only one?		