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The Role Of Individual Differences In Bilingual Language Processing

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Abstract

In this thesis, I investigated the neural correlates of bilingualism, and how individual differences in both brain and behaviour affect second language processing. To date, theories of bilingualism have tended to treat bilinguals as a uniform group, while in practice they vary greatly in both experience and ability. By examining how individual differences in proficiency and age of acquisition contribute to second language learning and processing, I sought to address this issue. In chapter two, I used event-related potentials to investigate how age of acquisition and proficiency modulate processing of a novel versus a grammatical rule that is similar across languages. I provided evidence that both age of acquisition and proficiency, in addition to bilingual status, modulate processing of a novel grammatical rule. In contrast, only proficiency predicted processing of a similar grammatical rule. Thus, while the similarities between languages affect second language processing, the degree of their influence is modulated by individual differences in second language experience. In chapter three, I used functional magnetic resonance imaging to investigate how bilinguals represent their shared, integrated lexicons in the brain. Several areas showed differing patterns of representation, while univariate analyses in these areas showed no differences in levels of activation. The separate representation of first and second languages in these regions provides a possible basis for the neurocognitive realization of a shared, integrated lexicon proposed by many theories of bilingualism. In chapter four, I used diffusion tensor imaging to investigate how AoA modulates white matter microstructure, examining white matter tracts in the left and right hemispheres that underlie language processing. Group statistics suggested that second language speakers as a whole may have lower fractional anisotropy, while the within-group analysis revealed that white matter integrity is sensitive to individual experience. Chapter five discusses the relevant findings of the previous chapters, and considers how individual differences arise. Next, I make recommendations for theories of bilingual language processing, and close with a discussion of future research directions.

Keywords

Bilingualism, language, individual differences, event-related potentials, functional magnetic resonance imaging, diffusion tensor imaging, grammar, lexicon

Co-Authorship Statement

The chapters of this dissertation are manuscripts that have been prepared for submission to scientific journals. The presented data are based on a series of collaborative research projects; however all manuscripts have been primarily written by Emily S. Nichols. Chapter 2 has been written in preparation for publication, authored by Emily S. Nichols and Marc F. Joanisse. Chapter 3 has been written in preparation for publication, authored by Emily S. Nichols, Yue Gao, Li Liu, and Marc F. Joanisse. Chapter 4 has also been written in preparation for publication, authored by Emily S. Nichols, Marc F. Joanisse, Yue Gao, and Li Liu.

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1   Introduction

The relationship between brain and behaviour in relation to bilingualism is just beginning to be understood. The majority of neurocognitive models of language processing have focused on that of a single language (Seidenberg and McClelland, 1989; McClelland and Patterson, 2002; Pinker and Ullman, 2002; Mcclelland et al., 2014), despite it being estimated that more than half the world speaks more than one language (Ansaldo et al., 2008; Grosjean, 2008). Although a number of models of bilingual language processing have been put forward, we currently lack a single comprehensive neurocognitive model. Such a model must include core aspects of language processing, specifically grammar and syntax, semantics, and phonology. In addition, it must include the domain-general processes required to successfully function in one language or the other; such cognitive processes include working memory, inhibitory control, and attention.

Additionally, individual differences in both brain and behaviour greatly affect second language (L2) processing. Learning an L2 is considerably easier and more successful when it begins early in life (Johnson and Newport, 1991). Indeed, many studies have shown both behavioural and brain differences in early vs. late L2 learners (Wartenburger et al., 2003; Pakulak and Neville, 2011; Newman et al., 2012; Nichols and Joanisse, 2016). However, there is ambiguity as to the source of these differences. We might interpret differences in the apparent neural organization of L2 learning as reflecting age-dependent differences in neuroplasticity, or they could simply reflect general differences in proficiency to which an L2 has been learned (Wartenburger et al., 2003; Newman et al., 2012; Nichols and Joanisse, 2016). The difficulty in disentangling the effects of age of acquisition (AoA) and proficiency on L2 learning lies in the fact that the two are frequently correlated such that earlier L2 learners generally achieve higher proficiency in their L2 (Johnson and Newport, 1989; Weber-Fox and Neville, 1996; Stevens, 1999; Pakulak and Neville, 2011).

Despite the correlation between proficiency and AoA, some late learners do indeed become proficient in L2. Late learners who achieve high proficiency appear

comparable in language function to native speakers. For example, highly proficient individuals, regardless of AoA, show an increase in the use of discourse markers and conjunctions, as well as higher fluency when compared to individuals with low proficiency (Neary-Sundquist, 2013). Highly proficient late L2 learners have also shown differences in brain activation from that of low proficiency late learners using neurophysiological and neuroimaging measures (Perani et al., 1998; Wartenburger et al., 2003; Gillon Dowens et al., 2011; Nichols and Joanisse, 2016). However, when controlling for proficiency, late learners still differ from early learners both in measures of timing (Pakulak and Neville, 2011; Meulman et al., 2015) and level of brain activity (Wartenburger et al., 2003; Nichols and Joanisse, 2016). Thus, differences in L2 processing could be due to either proficiency or differences in developmental neuroplasticity.

There is also the issue of how the cutoff for early and late AoA is determined. Past studies have used a variety of ages to categorize late AoA groups, ranging from 6 to 16 years of age. This means that early learners in some studies would be classified as late learners in others, and vice versa. There is still much debate about when the critical period ends, if it exists at all. Indeed, results supporting a critical period are confounded with other predictive factors, such as amount of L2 education, chronological age, and L2 language exposure (Flege et al., 1999). Instead, there may be no qualitative difference between early and late AoA, but rather that AoA has a graded effect in addition to, and independent of, the effect of proficiency (Nichols & Joanisse, 2016). Accordingly, treating AoA as a continuous variable may allow for a more complete and accurate description of the effects of AoA on L2 processing.

Thus, although current models have begun to account for cognitive processing data, there remain a number of factors, including individual differences, which must be considered in order to form a comprehensive neurocognitive model of L2 processing. The aim of this chapter is to describe in further detail why current models of L2 processing are problematic, and to offer suggestions on how to improve current theories of bilingual language processing, taking into account evidence from the brain. I will provide descriptions of three different factors that will inform models of neurocognitive bilingual

language processing; grammar, word recognition, and the brain's connectivity between areas involved. Finally, I will consider individual differences and how they might interact with these processes.

1.1 Differences between monolingual and bilingual language processing

1.1.1 Language acquisition experience

Monolingual and bilingual language processing can differ in fundamental ways, due in part to the different conditions under which each was learned. Most people acquire their first language (L1) with ease, under naturalistic settings and via mostly implicit learning (Houston, Santelmann, & Jusczyk, 2004; Jusczyk, 1999; Jusczyk, Houston, & Newsome, 1999; Saffran, Aslin, & Newport, 1996). However, there remain individual differences in L1 acquisition; children are raised in both language-impoverished and language-rich households, and monolingual adults do indeed differ in L1 proficiency levels (Newman et al., 2012). However, first exposure to L1 is largely considered to be from birth, and barring the presence of language disorders, most adults are relatively proficient in L1.

In contrast, learning an L2 can be a greater challenge, especially with increasing AoA (Stevens, 1999; Weber-Fox & Neville, 1996). There is also a wider range of circumstances in which L2 acquisition occurs. If a child is being raised in a balanced bilingual household, then both languages may be learned simultaneously. However, often one language is the dominant language in the household and the child receives unbalanced exposure. Additionally, the dominant language at home may differ from the dominant language in society, such as in the case of a Chinese family emigrating to Canada. Often, as is the case in schools, L2 instruction is explicit and begins at or after the age of five. In other cases, monolingual adults may decide to learn a new language, enrolling in a course or using language-instruction software. While none of these scenarios prevents an individual from becoming fully fluent in two or more languages, there remains an interaction between individual differences in learning experience, such

as instruction method and AoA, and ultimate language proficiency. Thus, both intrinsic and extrinsic individual experiences shape the way L1 and L2 are represented in the brain, and the independent contributions of each are difficult to disentangle (Newman et al., 2012; Nichols & Joanisse, 2016; Pakulak & Neville, 2011).

1.1.2   Conflict between languages

There is also the issue of conflict between languages. Bilinguals must contend with language-nonspecific access and competition between their two languages (Dijkstra, Grainger, & van Heuven, 1999; Haigh & Jared, 2007; Jared & Kroll, 2001; Jared & Szucs, 2002), creating a necessarily different language processing experience from monolinguals. That is, in addition to the difficulties L1 speakers experience such as resolving different speakers, accents, and coarticulatory cues, L2 speakers must inhibit the inappropriate language, while effectively communicating in the appropriate one. Much research has been dedicated to the role of inhibitory control in bilinguals, suggesting that this is an important mechanism in bilingual language processing (Costa, Santesteban, & Ivanova, 2006; Green, 1998; Linck, Schwieter, & Sunderman, 2012).

In addition to interference between languages, L1 and L2 differ in some constructs (e.g., Mandarin has tone, French has gender) but not others (e.g., cognates between English and French). Thus, L2 speakers need to resolve different aspects of each language, producing the correct response for the situation. L2 grammatical structure is more difficult to acquire than semantics (Hahne, 2001; Hahne & Friederici, 2001; Pakulak & Neville, 2011; Weber-Fox & Neville, 1996), while similarity between languages can aid in L2 grammar acquisition (Foucart & Frenck-Mestre, 2011; Hartsuiker et al., 2016). Monitoring and inhibitory control processes are thought to be involved in resolving conflict between languages, while monolingual language processing may not need to resolve conflict to the same degree.

1.2   Current theories of bilingual language processing

There are competing models of bilingual language processing that differ in their attempt to account for important aspects such as bilinguals' ability to maintain two

languages at once, effects of age of acquisition, and similarities across languages. Despite the numerous strengths of each model and theory, there remains a distinct lack of agreement on the mechanisms responsible for bilingual language processing, especially at the neural level. Especially difficult to account for is how neural representation of a bilingual's two languages is shaped by individual differences, due to the relative heterogeneity within bilinguals. Here, I discuss several models and theories of bilingual language processing and their relative strengths and weaknesses with regards to how they account for individual differences.

1.2.1   Bilingual Interactive Activation Plus Model

The Bilingual Interactive Activation Plus (BIA+; Dijkstra & van Heuven, 2002) model describes bilingual word recognition, and posits that two subsystems exist: a language processing system, and a task/decision system. The language processing system consists of orthographic, phonological, and semantic representations that are integrated across languages, and are present at the sublexical, lexical, and semantic levels. The different levels of representation are highly interactive; lexical access simultaneously activates both sublexical and semantic representations. Within the language subsystem there are also language "nodes", which are activated by the lexical level, and represent language membership, or the language to which the lexical input belongs. In contrast, the task/decision system is non-linguistic in nature. It comprises the necessary processing steps for completing the task (e.g., word identification) by allocating the required attention, inhibitory, and working memory resources. It receives input from the language system, and determines decision criteria and produces a response.

There is both behavioural and neuroimaging evidence to support the BIA+ model. The effect of cross-language priming has been used to support the assumption of an integrated lexicon and non-selective lexical access (Ando et al., 2015; Jouravlev, Lupker, & Jared, 2014; Midgley et al., 2008; Zhou et al., 2010). For example, numerous behavioural and event-related potential (ERP) studies have shown L1 priming L2 target words in both the phonological and orthographic modalities (Brysbaert, Van Dyck, & Van de Poel, 1999; Haigh & Jared, 2007; Lemhöfer & Dijkstra, 2004; Van Wijnendaele

& Brysbaert, 2002). Jouravlev and colleagues (2014) found L2-L1 cross-language priming at both the orthographic and phonological level between English and Russian, further confirming that L1 and L2 representations are integrated across languages. The BIA+ also accounts for individual differences in proficiency level; in unbalanced bilinguals, resting activation levels are lower in the non-dominant language (often L2) leading to slower word recognition. However as bilinguals become balanced in proficiency, resting activation levels become similar between languages, leading to symmetrical priming effects across languages. Several neuroimaging studies have also supported parallel access to an integrated lexicon, by demonstrating overlap of activation during word processing and simple sentence processing tasks (Briellmann et al., 2004; Chee, Tan, & Thiel, 1999; Yokoyama et al., 2006) However, the model is limited to sublexical, lexical, and semantic levels, and has yet to include a grammatical and syntactic mechanism that would provide a complete model of bilingual language processing. Additionally, the neural mechanisms underlying the BIA+ remain unclear, specifically how bilinguals are able to maintain a shared, non-selective lexicon in the brain.

1.2.2   Unified Competition Model

The Unified Competition Model (UCM; MacWhinney, 2005) is a model of first and second language acquisition, and the main tenet is that of competition between activating languages. The model proposes a processing system that selects between outputs based on their strength of activation. The strength of activation depends on multiple factors, including transfer between languages, cue strength, and resonance within the model. Competition takes place in many forms, including auditory, lexical, and morphosyntactic. This model describes several observations regarding L2 learning, such as transfer between L1 and L2 (Tolentino & Tokowicz, 2011, 2014) and how processing load affects sentence processing (Yokoyama et al., 2006).

Support for the UCM comes from behavioural, ERP, and neuroimaging research. Using eye-tracking, Tuninetti et al. (2015) demonstrated that in a syntactic task, number and strength of syntactic cues was a larger predictor of eye movements than native

language, in line with the UCM's component of cue strength. Although Tuninetti and colleagues found no evidence of cross-language transfer as revealed by eye movements, a number of studies have shown these effects using ERPs. While shared syntactic structures between L1 and L2 show similar ERP effects, differences arise when processing crosslinguistically dissimilar syntactic structures (Tolentino & Tokowicz, 2011; Vainio et al., 2014; Yokoyama, 2006). The UCM, therefore, provides a compelling model of bilingual language learning, supported by neural evidence. However, there is an ongoing challenge to determine how neural data map onto the tenets of the UCM and how competition changes with factors such as AoA. For example, while similarities between L1 and L2 facilitate L2 acquisition, it is unclear how this actually occurs in the brain, and how that might be affected by level of plasticity or learning environment.

1.2.3   The Revised Hierarchical Model

The Revised Hierarchical Model (RHM; Kroll and Stewart, 1994; Kroll et al., 2010) is a model of lexical processing that proposes an asymmetric mapping of words to concepts in bilingual memory. This model has been used to explain differences in performance between low and high proficiency L2 speakers, suggesting that a greater mismatch in proficiency between L1 and L2 leads to a greater asymmetry in word-concept mappings. Specifically, the RHM proposes a direct link from L2 to L1, as learned words in L2 have been mapped onto words in L1, but that there is an indirect link from L1 to L2, by way of the concept (Figure 1.1). Importantly, the RHM proposes separate lexicons for L1 and L2, with selective access to each.
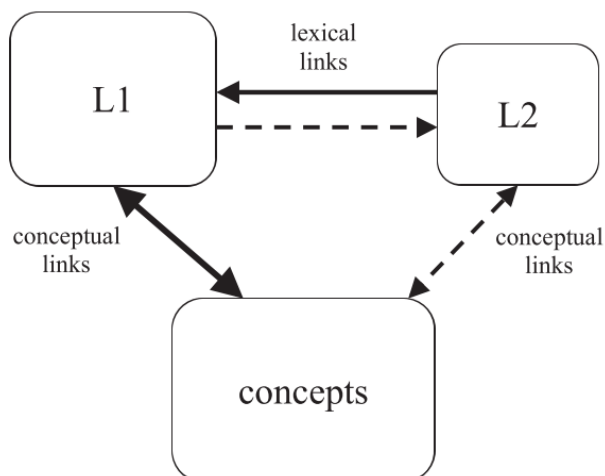
Figure 1.1. The Revised Hierarchical Model (RHM). The RHM proposes that words in L2 are mapped onto words in L1. L1 is indirectly linked to L2 by way of the shared concepts (Kroll & Stewart, 1994).

Issues have been raised with regard to the tenets of the RHM (Brysbaert & Duyck, 2010; Kroll et al., 2010). Research strongly suggests that bilinguals have an integrated lexicon, with non-selective access (Ando et al., 2015; Brysbaert, Van Dyck, & Van de Poel, 1999; Haigh & Jared, 2007; Jouravlev, Lupker, & Jared, 2014; Lemhöfer & Dijkstra, 2004; Midgley et al., 2008; Van Wijnendaele & Brysbaert, 2002; Zhou et al., 2010). However the main concept that there are asymmetrical connections between bilingual memory representations has been supported. Poarch and colleagues (2015) found that in Dutch speakers who were beginning to learn English, reaction times were shorter to translate words from L2 to L1 than from L1 to L2, suggesting that there are indeed asymmetric mappings between L1 and L2 and that the route from L1 to L2 is weaker. Similarly, Declerck et al. (2015) found stronger connections between concepts and their L1 lemma than between concepts and their L2 lemma. Thus, although the RHM in its current construction does not take into account an integrated lexicon and language non-selectivity, it offers an explanation of asymmetric translation effects.

1.2.4   Declarative/Procedural Model

Unlike the BIA+ and the Unified Competition Model, the Declarative/Procedural (DP) Model (Ullman, 2001) proposes that L1 and L2 are initially processed by differing underlying systems. L1 is processed by two underlying memory systems; that of declarative memory, upon which lexical memory depends, and that of procedural memory, upon which syntactic processing depends. In contrast, it assumes L2 is initially processed entirely by the declarative memory system reflecting a process of memorization. However, with increasing proficiency in L2, syntactic processes shift to the declarative/procedural system as individuals begin learning rules rather than memorizing words and phrases. This can be compared to the theory that children learn grammar initially via memorization, and then begin to generalize (Marcus, 1993).

The DP model builds upon studies that locate declarative memory to temporal structures (Hodges & Patterson, 1997; Squire, Knowlton & Musen, 1993; Squire & Zola, 1996, Ullman, 1997), while frontal and basal ganglia structures are thought to underlie procedural memory (Squire et al., 1993, Ullman, 1997). The model is supported by neuroimaging data showing greater temporo-parietal activity for L2 versus L1 in both right and left hemispheres of the brain during grammatical tasks but not semantic tasks (Dehaene et al., 1997; Perani et al., 1998, Wartenburger et al., 2003). Additionally, ERP effects of syntactic processing are more affected by AoA than semantic processing (Hahne & Friederici, 2001; Weber-Fox & Neville, 1996). The greater differences between L1 and L2 processing in syntactic, but not semantic, processing suggest that while the same underlying structures process semantic information (i.e., the declarative memory system), L1 and L2 syntactic processing relies on different structures. That is, while syntactic processing in L1 is procedural, in L2 it relies on declarative memory.

The DP model describes both syntax and semantics, and can account for the effect of individual differences on bilingual language processing. The cortical regions underlying the DP model have also been described. However, it is unclear how an L2 speaker makes the transition from declarative to procedural memory when acquiring L2 grammar. Additionally, the DP model claims that both L1 and L2 semantic processing

relies on declarative memory, and cannot account for proficiency and AoA effects in lexico-semantic processing. Although grammatical processing is more sensitive to L1/L2 differences, individual differences in L2 acquisition and fundamental differences in L1/L2 processing still modulate lexico-semantic processing (Newman et al., 2012; Nichols & Joanisse, 2016). Thus, the DP model remains an incomplete model of second language acquisition and processing.

1.2.5   Bilingual Dual-Coding Theory

The bilingual application of Dual-Coding Theory (DCT; Paivio & Desrochers, 1980), similar to the DP model, proposes separate verbal systems underlying L1 and L2, but includes a third imagery system to represent nonverbal objects and events which can be both separate and shared between languages. The two verbal systems interact through translation equivalents, and the single nonverbal system is connected with both verbal systems. The independence of verbal and imagery systems is best exemplified in that there are abstract words that have no nonverbal equivalents, while some experiences are difficult or impossible to describe verbally.

Both behavioural and neuroimaging data have supported the bilingual DCT. Culturally biased pictures are named faster in the culturally-relevant language than in the culturally unrelated language, suggesting that some image representations are more strongly connected to one language than the other (Jared, Poh, & Paivio, 2013). That is, when the North American depiction of "dragon" was presented, it was named faster in English than in Mandarin; similarly, the Chinese depiction of "dragon" was named faster in Mandarin than in English. Other studies have focused on the implications of DCT on concrete versus abstract words in a single language. Topographic distributions in ERP responses to abstract words are more left lateralized than concrete words (Binder et al., 2005; Kounios & Holcomb, 1994); high imagery words have faster response times and show different patterns of activation in bilateral occipital regions of the brain (Lee et al., 2014). Together, these results have been taken to support DCT by suggesting that imagery is an important part of language processing, and may affect each language differently. However, while neural correlates in line with the DCT's predictions have

been observed, the actual neural mechanism underlying the relationship between imagery and language remains to be described, along with the influence of individual differences on this relationship. The DCT also does not describe sentence-level syntactic processing, or the observed relationship between L1 and L2 syntactic similarities and dissimilarities.

Thus, there are several strong models of bilingual language processing, sharing several main ideas. The evidence for a shared, integrated lexicon is overwhelming, and most models have acknowledged the importance of its inclusion. Several models also stress the importance of transfer between L1 and L2, based on neural correlates of shared versus differing constructs. However, while some models attempt to describe the main aspects of bilingual language processing, such as grammar and semantics (e.g., the UCM), others focus solely on word processing (e.g., the BIA+ and the RHM). Each model uses neurophysiological and neuroimaging results to support its predictions, describing brain structures that may underlie the processes it describes, often referring to the same work, and mostly agreeing on the brain regions and ERP components involved. Although several brain regions are agreed to support bilingual language processing, such as the left inferior frontal and superior temporal gyri, the neural mechanisms that engage these areas, leading to the observed behaviour of bilingual language comprehension and production, remain to be described. Finally, bilingual language acquisition is heterogeneous across learners, thus the described models must also be able to account for the influence of both endogenous and exogenous factors on each aspect of the model.

1.3   Research questions

My central objective is therefore to better articulate how individual differences in proficiency and AoA contribute to second language learning and processing, while understanding the neural mechanisms underlying different linguistic processes. By taking a largely individual differences approach in describing grammatical processing and word recognition, I will consider how variation in behaviour relates to variation in neural mechanisms supporting bilingualism.

While proficiency and AoA are known to affect L2 processing, specific characterization of their effects on different parts of language is lacking. Both factors are often investigated in isolation, and discrete groups are created from inherently continuous variables. Thus, I will discuss three different aspects of L2 language acquisition and processing which deserve greater understanding. In chapter 2 I will describe the individual contributions of proficiency and AoA on grammatical processing, using grammatical structures that are and are not present in the bilinguals' L1. In chapter 3 I will describe how L1 and L2 are represented differently within language processing areas in the bilingual brain. In chapter 4 I will describe how underlying white matter connectivity changes with proficiency and AoA, drawing connections between previous findings in bilingual research of differential activity and the possible neuroanatomical mechanisms responsible.

The goal of my dissertation is to describe current models of bilingual language processing and to provide suggestions for future models based upon both neural evidence and individual differences. The first study of my dissertation will use ERPs to examine French L2 grammatical gender processing in native speakers of English, who do not posses a grammatical gender system in L1. Study two will discuss a study in which I examined how the brain represents bilinguals' two languages within language processing areas, describing a neural mechanism to support the observation of an integrated lexicon. Study three will investigate how individual differences affect white matter tracts in the bilingual's brain, describing how cortical areas involved in bilingual language processing may depend upon the connections between them. The general discussion will integrate each of these studies into a series of results and suggestions for future neurocognitive models of L2 acquisition and processing.

1.3.1   What factors influence learning of novel grammatical rules in bilinguals?

In Chapter 2, I investigate how AoA and proficiency affect the learning of novel grammatical rules in bilinguals. Research suggests that individuals who learn an L2 can often use knowledge of their L1 to aid them in their L2 (Foucart & Frenck-Mestre, 2011;

Hartsuiker et al., 2016), but many languages contain aspects of grammar that others do not. Inflectional morphology varies greatly across languages; not only do different morphological systems exist in different languages (e.g., pluralization, gender), but different languages also employ similar morphological systems differently (Aronoff, 1994). The lack of clear mapping from one language to another may be one reason why inflectional morphology tends to be a particularly difficult part of L2 learning (Pakulak & Neville, 2011). Thus, a neurocognitive model of L2 processing must be able to account for these observations. Indeed, models such as the UCM (MacWhinney, 2005) consider L1-L2 transfer to be central to L2 processing. Additionally, research has demonstrated effects of proficiency and AoA on how L2 grammar is processed (Pakulak & Neville, 2011; Foucart & Frenck-Mestre, 2011; Gillon Dowens et al, 2011), indicating that individual differences must also be considered.

In the first study of my dissertation, we used ERPs to examine French L2 grammatical gender processing in native speakers of English, who do not possess a grammatical gender system in L1. Of interest was whether individual differences in L2 proficiency and AoA influenced these effects. L2 learners and native speakers of French read French sentences that were grammatically correct, or contained either a grammatical gender or word order violation, and produced different effects of grammatical gender and structure violations. The results speak to theories that emphasize L1-L2 grammatical transfer, while describing how different individual factors contribute to how a novel grammatical rule is learned.

1.3.2   Which brain areas are involved in bilingual language representation?

In Chapter 3, I used RSA to investigate whether areas involved in word recognition distinguish between languages. Proficient bilinguals are typically skilled at the seemingly complex task of keeping their two languages separate; they are able to function in one language without much intrusion from the other. Past research has provided much evidence that L2 relies on similar brain areas involved in processing L1 (Indefrey, 2006; Perani et al., 2003; Wang et al., 2011). Even when differences exist in

brain activity for L1 and L2, there remains extensive overlap, such that regions of dissociation often occur outside the margins of the classical language network (Indefrey, 2006). Within regions that do not differentiate between L1 and L2 using typical univariate analyses, the general conclusion is that these regions are processing L1 and L2 similarly given similar levels of activity for both languages. However, because univariate analyses of fMRI data cannot inform us of how information is being represented, this conclusion may be incorrect. Bilinguals, including those who do not show neural differences between L1 and L2, are still able to keep separate their two languages, suggesting that there may be some degree of separation of the two languages in the brain. For instance, it is generally accepted that bilinguals have a single, integrated lexicon (see van Heuven & Dijkstra, 2010, for a review), and while neuroimaging provides much support for an integrated lexicon through activation of similar structures, the separation of the pattern of activity within the shared L1/L2 brain areas may provide evidence that bilinguals represent words separately for both languages.

In order to understand how bilinguals maintain an integrated yet separable lexicon, especially when differences in brain activation are absent, research must examine how the languages are being represented within the language-processing network. To address this I used Representational Similarity Analysis (RSA), which allowed us to determine whether L1 and L2 were distinctly represented at the level of neural populations. RSA is an fMRI analysis technique relying on reproducible spatial patterns of activity that correlate with distinct experimental conditions (Kriegeskorte et al., 2008). RSA has been used to reveal differences between conditions within individual brain regions that were previously undetectable using standard univariate methods; it reveals cortical patterns sensitive to stimulus patterns even when there is no apparent difference in degree of activation. The results describe how the brain supports an integrated lexicon, a recurring theme in models of bilingualism, linking previous observations of cross-linguistic priming to actual representation of the integrated lexicon in the brain.

1.3.3   What factors influence connectivity within the bilingual brain?

It has been proposed that L2 learning requires increased neural resources due to maturational changes in neural plasticity within pathways supporting L1 learning (Mohades et al., 2012; Nichols & Joanisse, 2016). This is usually measured by comparing the size and extent of brain region activation for either language, however this may tell only part of the story. For instance, more activation could be due to compensatory resources needed when processing a more difficult language. Connectivity may provide a better way to understand neural efficiency in L2 language processing. Concordant with this view, studies have found that age-of-acquisition (AoA) modulates structural connectivity, as measured using diffusion tensor imaging (DTI). A common measure of white matter microstructure is fractional anisotropy (FA), which ranges from zero to one and is interpreted as indexing the cohesiveness of white matter tracts. High FA suggests that water diffusion is restricted to a single direction, which corresponds to greater myelination of the white matter tract (Pierpaoli & Basser, 1996), promoting faster neural transmission, and highly organized directionality or coherence of white matter (Mädler et al., 2008). Low FA suggests that water diffusion is unrestricted and that the tract is less myelinated and coherent, leading to less efficient signal transmission. FA varies with AoA such that children who learned two languages from birth (simultaneous bilinguals) show higher white matter integrity in the left inferior fronto-occipital fasciculus (IFOF), the tract connecting anterior frontal regions with posterior temporal regions when compared to children who learned their two languages sequentially (Mohades et al., 2012). However, lower integrity was also found in the tracts projecting from the anterior portion of the corpus callosum to orbitofrontal cortex compared to late L2 learners. Similarly, in a study by Nichols and Joanisse (2016), increasing AoA was correlated with higher white matter integrity, however the specific tracts that showed this positive relationship between AoA and FA conflict with the tracts in Mohades et al. (2012). These results highlight how differences in brain connectivity may be related to L2 AoA, however the relationship of AoA and specific white matter tracts is unclear. In fact at least one proposal maintains that there are separate L1 and L2 networks that are complementary in their importance as a function of AoA (Mohades et al., 2012). The

differing influence of AoA on separate tracts may reflect their relative importance in L1 vs. L2 processing.

Chapter 4 therefore investigates the differences in monolingual and bilingual white matter integrity, and the relationship between individual differences in AoA and white matter microstructure. We acquired measures of AoA from 22 monolingual English speakers and 20 English-Mandarin L2 speakers, along with their DTI scans. We first contrasted FA between groups in four bilateral tracts known to underlie bilingual language processing: the arcuate fasciculus, the inferior fronto-occipital fasciculus, the superior longitudinal fasciculus, and the inferior longitudinal fasciculus. Next, we examined how AoA in the L2 group related to white matter integrity in the tracts that showed differences between groups. Results speak to theories such as the DP model, which suggest that the underlying subsystems in the bilingual brain change to become similar to L1 as a factor of individual differences.

1.4 Summary

A neurocognitive model of bilingual language processing must take into account different areas of language processing such as grammar, semantics, and phonology. It also must take into account how the brain functionally and structurally supports each of these factors, and how the function and structure of the brain changes and is changed by the bilingual experience. Future research should focus on understanding this complex relationship between brain and behaviour.

The aim of the present review was to identify issues with the current state of theories and models of L2 processing. Although there are a number of current models that have been developed, we still do not have a comprehensive neurocognitive model that takes into account individual differences. As outlined, individual differences must be included in any model of L2 processing. Although many factors are tightly intertwined, such as AoA and proficiency, there are separable effects of each that must be considered. There is a complex interplay of both brain and behaviour, and evidence that each shapes the other.

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2 Individual differences predict ERP signatures of second language learning of novel grammatical rules

2.1 Introduction

Learning a second language is considerably easier and more successful when it begins early in life (Johnson & Newport, 1991). Indeed, many studies have shown both behavioural and neural differences in early vs. late L2 learners (Newman, Tremblay, Nichols, Neville & Ullman, 2012; Pakulak & Neville, 2011; Wartenburger, Heekeren, Abutalebi, Cappa, Villringer & Perani, 2003). However, there is ambiguity as to the source of these differences. We might interpret differences in the apparent neural organization of second-language learning as reflecting age-dependent effects of neuroplasticity, or they could simply reflect the general proficiency with which a second language has been learned (Newman et al., 2012; Wartenburger et al., 2003). The difficulty in disentangling the influences of age of acquisition (AoA) and proficiency on L2 learning is the fact that the two tend to correlate to some extent such that earlier L2 learners generally achieve higher proficiency in their second language (Johnson & Newport, 1989; Pakulak & Neville, 2011; Stevens, 1999; Weber-Fox & Neville, 1996).

Bilingualism research has explored many areas of second language acquisition and speaking, in both similar and dissimilar languages, however one area that is lacking a large body of literature is that of grammatical gender. There is research suggesting that individuals who learn a second language can often use knowledge of their first language to aid them in their second (Foucart & Frenck-Mestre, 2011; Hartsuiker, Beerts, Loncke, Desmet & Bernolet, 2016), but many languages contain aspects of grammar that others do not. Inflectional morphology varies greatly across languages; not only do different morphological systems exist in different languages (e.g., pluralization, gender), but different languages also employ similar morphological systems differently (Aronoff, 1994). The lack of clear mapping from one language to another may be one reason why inflectional morphology tends to be a particularly difficult part of L2 learning (Pakulak & Neville, 2011).

Grammatical gender systems, which classify nouns as masculine, feminine, or sometimes neuter, are present in many of the world's languages. In those languages that contain gender systems, there is sometimes overlap in article-noun gender agreement between languages, which can facilitate learning of noun genders; for instance the word *table* is feminine in both French and Spanish (i.e., *la table/la mesa*; Foucart & Frenck-Mestre, 2011, Paolieri, Cubelli, Macizo, Bajo, Lotto & Job, 2010). However, the situation may be different for a native speaker of a language that does not have grammatical gender. Current data suggest that L2 speakers with a grammatical gender in L1 show higher accuracy in both gender assignment and pronoun-noun gender agreement in L2 compared to L2 speakers without grammatical gender in L1 (Sabourin, Stowe, & de Haan, 2006).

The present study examines the joint contribution of proficiency and AoA to learning grammatical gender in L2. Proficiency is defined as the competence and facility in a second language. It is admittedly correlated with AoA (Stevens, 1999); however, some late learners do achieve high proficiency, and may appear comparable in fluency to early learners and native speakers. For example, highly proficient individuals, regardless of AoA, show an increase in use of discourse markers and conjunctions, and higher fluency when compared to individuals with low proficiency (Neary-Sundquist, 2013). Highly proficient late L2 learners have also shown differences in language-related brain activity from that of low proficiency late learners (Caffarra, Molinaro, Davidson, & Carreiras, 2015; Gillon Dowens, Guo, Guo, Barber, & Carreiras, 2011; Kotz, 2009; Perani, Paulesu, Sebastian Galles, Dupoux, Dehaene, Bettinardi, Cappa, Fazio, & Mehler, 1998; Stowe & Sabourin, 2005; Wartenburger et al., 2003). In addition, when controlling for proficiency, late learners still differ from early learners both in measures of timing (Meulman, Wieling, Sprenger, Stowe & Schmid, 2015; Pakulak & Neville, 2011; Rossi, Kroll, & Dussias, 2014) and level of brain activity (Wartenburger et al., 2003). Thus, differences in L2 processing could be due to either behavioural proficiency or true differences in neuroplasticity.

In addition to the effects of proficiency and AoA, some prior work also suggests that L2 learners process inflectional agreement - such as gender - differently from native

speakers. Lemhöfer, Spalek, and Schriefers (2008) investigated whether German-Dutch bilinguals performed differently on tasks where the gender of a noun was the same in both languages, compared to when the gender differed. In both a lexical decision task and a picture-naming task, reaction times were faster for gender-congruent trials than for gender-incongruent trials. The authors attributed this to an interaction between grammatical gender systems in the two languages, with facilitation occurring when the genders are congruent. These results have been supported by numerous studies in several different languages (Foucart & Frenck-Mestre, 2011; Paolieri, 2010; Salamoura & Williams, 2007), suggesting that the effect is quite robust among languages containing grammatical gender systems, although conflicting results have also been found (Costa, Kovacic, Franck & Caramazza, 2003).

The majority of the behavioural research surrounding grammatical gender in L2 speakers has focused on adult learning of a gender system. In an experiment by Alarcón (2011), behavioural measures of written comprehension and oral production were used to investigate whether English adult L2 learners of Spanish can acquire gender in their grammar. Results of these measures indicated that at high proficiencies, late (post-puberty) L2 learners showed no difficulty with grammatical gender, similar to native speakers. Similarly, Keating (2009) found that adult learners of Spanish produce higher rates of gender agreement errors with increasing distance between the adjective and noun. However, other studies have shown conflicting evidence, with adult learners experiencing difficulty in acquiring grammatical gender (Arnon & Ramscar, 2012; Montrul, Foote, & Perpiñán, 2008).

The many observed interactions between first and second languages in L2 speakers raise the question of how grammatical gender is learned in individuals whose L1 does not contain a grammatical gender system. Indeed, many of the world's most-spoken languages (e.g., English, Mandarin, Cantonese) do not possess a gender system, and studies examining L2 grammatical gender learners who do not possess a grammatical gender in their L1 have focused on late learners (Foucart & Frenck-Mestre, 2012; Gillon Dowens et al., 2011). The lack of research focusing on early learners leaves open the question of how AoA specifically affects learning of novel syntactic constructions.

ERP provides an ideal mechanism for studying grammatical relationships in first- and second-language processing (Caffarra & Barber, 2015; Foucart & Frenck-Mestre, 2012; Meulman et al., 2015; Morgan-Short, Sanz, Steinhauer & Ullman, 2010; Newman et al., 2012; Osterhout & Holcomb, 1992; Pakulak & Neville, 2011; Rossi et al., 2014; Silva-Pereyra, Gutierrez-Sigut, & Carreiras, 2012; Tanner et al., 2013). ERPs represent electroencephalography (EEG) signals that are time-locked to sensory or cognitive events. The high temporal resolution of ERPs allows the researcher to observe neural processing of language as it unfolds over time. This is in turn allows us to pinpoint changes in neural processes corresponding to a particular manipulation and isolate the moment at which they occur, typically well before the moment individuals can make an overt judgment of the stimulus or execute a behavioural response. In particular, grammatical violation tasks involve showing subjects sentences which are either grammatically congruent or contain a grammatical violation. For example, the sentence "*He took the whistling teapot off the of stove*" contains a grammatical violation of phrase structure that evokes predictable modulations in ERPs time locked to the onset of the violation. There are several possible grammatical violations, including phrase structure, number, tense, and, most relevant to the present study, grammatical gender. Manipulating the type of violation allows us to isolate processing of specific aspects of grammatical processing.

One ERP component that is sensitive to grammatical violations is the Left Anterior Negativity (LAN), a negative-going component with a left-anterior distribution (Molinaro, Vespignani, & Job, 2008; Neville, Nicol, Barss, Forster & Garrett, 1991; Pakulak & Neville, 2011). The LAN is thought to reflect early syntactic integration or first-pass grammatical processing (Friederici, Pfeifer & Hahne, 1993; Rösler, Pütz, Friederici & Hahne, 1993). Although the time-course is similar to the N400, the LAN possesses a different topography and is evoked in response to syntactic rather than semantic errors (however see Tanner, 2014 for a discussion). The LAN is often followed by a P600, a positive going component with a centro-parietal distribution that occurs approximately 600 ms post-stimulus onset. It is thought to reflect second-pass grammatical processing (Hahn & Friederici, 1999) or syntactic reanalysis (Kaan, Harris, Gibson & Holcomb, 2000). By manipulating the grammaticality of a sentence, the P600

has been shown to vary in its amplitude as well as its scalp distribution (Kotz & Friederici, 2003; Molinaro et al., 2008; Pakulak & Neville, 2011).

ERP markers of grammatical gender processing have been widely explored in monolingual speakers of languages that incorporate grammatical gender. Gender agreement violations have been found to elicit both a LAN and a P600 in native speakers of numerous languages including German, Italian, Dutch, and Spanish (Barber & Carreiras, 2005; Gunter, Friederici, & Schriefers, 1996; Molinaro et al., 2008; Sabourin & Stowe, 2008). As the LAN and the P600 are markers of syntactic violation processing, it can be concluded that the brain processes grammatical gender agreement violations much like other forms of syntactic violations, though the timing and scalp distribution of these effects has been found to vary (Barber & Carreiras, 2005; Gillon Dowens et al., 2011; Molinaro et al., 2008).

Syntactic ERPs described above have also been used to evaluate the time-course and native-like characteristics of L2 syntactic processing. Of note to the present study, some researchers have used these effects to argue for differences in how L2 learners detect grammatical violations. For instance, L2 learners might tend to show reduced or absent LAN and/or P600 effects in response to violations in grammatical structures known to be difficult for these individuals. Although results previously attributed to AoA may in fact be due to proficiency, several L2 ERP studies attribute these results solely to AoA. Pakulak and Neville (2011) investigated whether AoA affects syntactic processing, holding proficiency constant. A native English group and a high proficiency, late acquisition L2 English group performed a sentence comprehension task with phrase structure violations while their EEG was being recorded. The researchers found both a LAN and a P600 in response to syntactic violations in the native group, but found only a P600 in the late-learners, suggesting that late learners are not integrating incoming syntactic information in the same way as native speakers, perhaps relying on different neural mechanisms due to maturational constraints.

Similarly, some studies have specifically used ERPs to study grammatical gender in L2 speakers. A study by Morgan-Short and colleagues (2010) examined second

language learning of gender using an artificial grammar, in both implicit-learning (immersion-like) and explicit-learning (classroom-like) settings. The researchers tested subjects first at low proficiency and again at high proficiency, and found that when subjects viewed article-noun gender agreement violations at low proficiency, an N400 component, a negative going ERP component typically thought to reflect lexical-semantic violations, was elicited in only the implicit-learning group. At high proficiency, however, noun-article gender agreement violations elicited P600 in both groups. The authors suggest that from these results, it can be inferred that both proficiency and training affect inflectional morphological processing in L2 learners. Evidence from this study suggests that level of proficiency in late learners affects how the brain processes grammatical gender, implying that it may be possible to attain native-like processing of grammatical gender regardless of AoA, depending on the level of proficiency attained.

These results are supported by findings from Gillon Dowens et al. (2011), in which gender processing was studied using a group of late acquisition Spanish learners who spoke Mandarin as a first language. The authors sought to characterize gender processing in proficient L2 speakers who did not have a gender system in their L1. Subjects viewed sentences containing gender agreement violations while their EEG was recorded. As in the Morgan-Short et al. (2010) study, results indicated that a P600 component was elicited for gender agreement violations in this group. However, neither experiment had an L1 group to which they could compare their L2 results. This leaves undetermined how L2 speakers' ERPs response to gender agreement violations compare to those of native speakers. More recently, Meulman and colleagues (2015) found that AoA influences the ERP response to grammatical gender violations but not to verb agreement violations, suggesting that similarities between grammatical constructs in L1 and L2 may drive differences in the effect of AoA on grammatical processing.

That said, there are few studies directly comparing grammatical gender in L2 and L1 speakers of the same language. Foucart and Frenck-Mestre (2011) compared German-French bilinguals and native French speakers on a grammatical gender task. The authors manipulated gender agreement in French sentences, and found that violations elicited similar P600 effects in both groups, and also found that the P600 was larger for words

whose gender was the same across languages. The authors suggest that syntactic processing in a second language is affected by similarities between L1 and L2. While these findings describe language transfer effects between two languages that possess grammatical gender systems, these results cannot be generalized to second language speakers who do not have a gender system in their native language. However, a follow-up study in 2012 by the same authors found that both native French speakers and high proficiency, late acquisition English-French learners showed P600s in response to grammatical gender violations in spite of the fact that English does not have grammatical gender. The authors concluded that late L2 learners are able to acquire grammatical features not present in L1 (Foucart & Frenck-Mestre, 2012).

2.1.1   Rationale for the Current Study

While previous research suggests that high proficiency L2 or early AoA speakers process gender agreement violations differently from low proficiency or late AoA speakers respectively, there has been very little research comparing gender processing in L2 speakers to that in L1 speakers, especially across languages that do not both have a gender system. Further, research to date has tended to examine AoA and proficiency in isolation, leaving open the question of which of the two factors can best explain apparent differences, or whether maturational constraints and proficiency interact (Nichols & Joanisse, 2016). We addressed this issue by examining ERP indices of grammatical gender agreement violations in L2 learners of differing proficiencies and AoAs, compared to those of native speakers. Additionally, a grammatical word order (i.e., structural) violation condition was used in order to determine whether the similarity of a grammatical feature in L1 and L2 affects acquisition of L2 grammar. Because the structural violations we employed here can exist in both English and French, it was possible to compare the effect of AoA and proficiency on grammatical gender to their effect on a rule system that is similar across both L1 and L2, allowing us to determine whether there is a difference between learning a novel rule vs. simply learning a new language.

In line with previous studies showing independent effects of AoA and proficiency but also of group (e.g., bilingual vs. monolingual; Newman et al., 2012; Nichols & Joanisse, 2016), we predicted that in native and high proficiency L2 speakers, gender agreement violations would elicit both a LAN and a P600, and that the amplitudes of these effects would decrease with decreasing proficiency. We also predicted that at earlier AoA, L2 speakers would have large LANs and P600s, again similar to native speakers. But as AoA increases, amplitude would decrease (Meulman et al., 2015; Hahne & Friederici, 2001; Chen et al., 2007; Ojima et al., 2005; Weberfox & Neville, 1996). Such findings of separable contributions of AoA and proficiency would lend support to the theory that both AoA and proficiency play independent roles in the processing of grammatical gender in L2.

Structure violations were predicted to evoke both a LAN and P600, but AoA should not modulate the magnitude of these effects (Hahne, 2001; Hahne & Friederici, 2001; Neville et al., 1991, Newman et al., 2007; Rossi et al., 2006; Weber-Fox & Neville, 1996). The reason for this is that this type of syntactic error is possible in both English and French, thus AoA of L2 should not influence processing (MacWhinney, 1987, 2005). We also predicted an increase in LAN and P600 amplitude with proficiency regardless of L1/L2 status, as the error would be more egregious to higher proficiency French speakers. If there are indeed different effects of AoA and proficiency between grammatical gender and structure violations, it would suggest that while it is possible for L2 speakers to acquire novel grammatical rules, this process is different to learning grammatical rules that are present in L1.

2.2   Method

2.2.1   Subjects

Forty right-handed neurologically healthy adults were recruited from the University of Western Ontario community. Twenty L1 speakers (16 female) were individuals who reported learning French as their first language, ranging in age from 18 to 38 ($M = 23$, $SD = 5.3$). An additional 20 (14 female) L2 speakers were individuals who reported learning English as their first language and French at any point after English,

ranging in age from 18 to 33 (*M* = 21, *SD* = 3.8). A summary of group descriptives is provided in Table 2.1, and an extended description of the L2 speakers is available in Appendix A.

Table 2.1. Group demographic and behavioural measures

Measure		Group Mean (SD)		*t*(df)	*p*
		L1	L2		
AoA in years		0 (0)	7.20 (3.85)	-8.37(19)	< .001
Proficiency (% correct)		87.65 (9.76)	64.05(15.69)	5.71(31)	< .001
Sentence Comprehension Accuracy (% correct)	Control	86.00 (5.22)	79.88 (8.98)	2.64(30)	.013
	Gender	83.88 (21.62)	26.00 (20.12)	8.76(37)	< .001
	Structure	95.33 (6.14)	83.72 (16.25)	2.99(24)	.006
	Filler	87.36 (6.94)	77.60 (11.89)	3.17(30)	.003
Number of trials included in final analysis (out of 40)	Control	32.2 (3.97)	29.55 (4.03)	2.09(38)	.043
	Gender	31.5 (8.62)	9.80 (6.77)	8.85(36)	< .001
	Structure	36.15 (2.80)	32.10 (6.46)	2.57(26)	.016

Note: One-sample t-test used to test L2 AoA against 0. Welch's t-test used to test L1 vs. L2 for all other measures due to unequal variances between groups.

2.2.2   Materials and Procedures

In order to assess AoA, all subjects completed a detailed language history questionnaire in French, which inquired about past and present exposure in both their first and any second languages, shown in Appendix B. To assess proficiency, all subjects completed an intensive proficiency test which assessed both grammar and vocabulary proficiency. The French proficiency test was issued by pen-and-paper, and consisted of 100 questions. The test was designed by the French department at the University of Western Ontario to place non-native French speakers in the appropriate class. Scores correspond to the Common European Framework of Reference for Languages, levels A-C, with a score of 78% or greater corresponding to native-like proficiency, and 88% or greater corresponding to high native-like proficiency. Sixty-one questions were on

grammar; this section had participants complete sentences by choosing the correct grammatical form, covering the eight parts of speech (e.g., noun, verb, adjectives) as well as three grammatical tenses; the *passé composé*, *participle passé*, and *présent de l'indicatif*. The grammar section also covered the negative form, requiring answers to questions in the negative. Thirty-nine questions were on vocabulary. This section had several subsections in which participants completed sentences by choosing the correct, noun or verb to fit the context, perform verb-to-noun and noun-to-verb conversion, complete the opposite logical expression of a given statement, choose the correct name to describe inhabitants of a certain city or country, and finally to complete common proverbs. Completion of the test took approximately 50 minutes. An abridged version of the Edinburgh Handedness Inventory (Oldfield, 1971) was used to verify handedness.

Stimuli in the experimental task consisted of 160 sentences, with 40 containing article-noun gender agreement violations (*J'ai nagé dans $\underline{le^m\ piscine^f}$ tous les jours /I swam in $\underline{the\ pool}$ every day*), 40 well-formed sentences containing no violations (*J'ai nagé dans $\underline{la^f\ piscine^f}$ tous les jours /I swam in $\underline{the\ pool}$ every day)*, and 40 sentences containing structural violations in which two words were switched such that the grammatical structure was incorrect but the gender agreement was intact (*J'ai nagé dans $\underline{piscine^f\ la^f}$ tous les jours /I swam in $\underline{pool\ the}$ every day)*. Experimental sentences were counterbalanced across subjects, with the sentences that contained gender violations for a third of the subjects being the sentences that contained either no violations or structure violations for the other two thirds. An additional 40 well-formed filler sentences were used which remained the same between counter-balanced lists and were used to ensure equal numbers of violation and well-formed sentences. Experimental items are available in Appendix B, with seven of the sentences taken from Baudiffier and colleagues (2011).

Sentences were presented visually in the center of a CRT screen, word-by-word, using rapid serial visual presentation (RSVP). Words were on-screen for 300 ms with a 200 ms gap, and following each sentence subjects were asked whether the sentence was well-formed via a visual cue *"Est-ce une bonne phrase Française?"*(*"Is this a good French sentence?")*. Yes/no responses were made via button-press. Sentences were presented over four blocks of 40 sentences each, with half containing violations. Prior to

the experimental trials, subjects completed a practice block of 5 sentences, which they were allowed to complete as many times as they wished.

2.2.3   EEG Recording and Preprocessing

Stimuli were presented using the E-Prime 2.0 software package (Schneider, Eschman, & Zuccolotto, 2002). Continuous EEG data was collected using BioSemi software from 32 scalp electrodes (Fp1/2, AF3/4, F7/8, F3/4, T7/8, C3/4, CP5/6, CP1/2, P7/8, P3/4, PO3/4, O1/2, Fz, Cz, Pz, Oz) and two mastoid electrodes, and electrooculogram (EOG) was recorded from four face electrodes placed above and below the left eye and on the outer canthus of each eye using the BioSemi ActiveTwo EEG system consisting of amplifier-embedded Ag/AgCl electrodes arranged according to the International 20-30 system. A Common Mode Sense active electrode and a Driven Right Leg passive electrode were used as the ground. Data was recorded in the frequency range of 0.1-100 Hz at a 512 Hz sampling rate, with impedances below 20 kΩ.

ERP data was processed using EEGLAB software (Delorme & Makeig, 2004) and the ERPLAB add-on software (Lopez-Calderon & Luck, 2014). After importing the data, EEG data underwent a .1 – 30 Hz bandpass filter with a 60 Hz notch filter to remove line and muscle noise. EEG data was segmented into -200 – 1000 ms single-trial epochs of each critical word in each condition of interest (gender violation, structure violation, control) and baseline corrected to a pre-stimulus baseline (-200 – 0 ms). Critical words consisted of the noun immediately following the gender cue (correct vs. incorrect), and the first word in a syntactically reversed grammatical violation. Artifacts were removed by excluding epochs from analysis in which voltage exceeded -100 – 100 μV at any scalp electrode. In order to ensure that we were analyzing sentences in which the violation was detected, only sentences that were responded to correctly were included in analyses. Filler sentences were used in order to equate the number of correct sentences with the number of violation sentences and were thus excluded from analysis. Total number of trials included in the final analysis after rejecting artifacts and incorrect trials are described in Table 2.1.

To examine the LAN, mean amplitude between 300 – 500 ms was computed for each electrode. Electrodes were grouped into regions of interest arranged in a 3 x 3 grid over the scalp (left/midline/right and anterior/center/posterior), and data from each electrode within an ROI were treated as repeated measures of that ROI. To ensure that the violation conditions were eliciting the LAN, difference waves were computed from each type of violation minus the control condition and amplitudes were submitted to linear mixed effects (LME) analysis with condition (gender violation minus control/structure violation minus control), group (L1 speaker/L2 speaker), and ROI as fixed effects and subjects as a random effect. We then assessed AoA and proficiency on the amplitude of the LAN. A forward stepwise procedure was then performed on mean amplitude of the difference waves, examining the independent contributions to a LME model with ROI and group as fixed effects, AoA and proficiency as continuous effects, and subjects as a random effect. The predictor explaining the most variability was assessed using AIC values, and a drop-one procedure was used to compute whether a single term could be removed from the model at each step without significantly reducing the model's explanatory value. The final model contained (stepwise) the variables that explained significant variability in the data, excluding variables that could be removed without influencing the model.

To examine the P600, mean amplitude between 500 – 800 ms was computed for each condition over the same nine ROIs. Similar to the LAN, we submitted difference wave amplitudes to LME analysis with condition (gender violation minus control/structure violation minus control), group (L1 speaker/L2 speaker), and ROI as fixed effects and subjects as a random effect in order to ensure that the violation conditions were eliciting a P600. Again, to assess the effect of AoA and proficiency on the amplitude of the LAN, a forward stepwise procedure was performed on difference wave amplitudes, examining the independent contributions of electrode, group, AoA, and proficiency to an LME model.

Because our participants ranged in proficiency, we expected a large range of accuracy in performance on the violation detection task, leading to some participants having more trials than others included in the analysis. The LME modeling approach

used here helped address potential issues this might raise with some types of statistical analyses; LME models include both fixed effects and random effects and can account for unbalanced data and nonsphericity (Baayen, Davidson, & Bates, 2008; Bagiella, Sloan, & Heitjan, 2000). For these reasons they are ideal for ERP data, especially in designs that lead to necessarily unbalanced data (Tibon & Levy, 2015). The present study used the *lme4* (Bates et al., 2016, version 1.1-12) and *LMERConvenienceFunctions* (Tremblay & Ransijn, 2015, version 2.10) packages for R (R Core Team, 2015, version 3.2.2).

2.3 Results

2.3.1 Behavioural

Group measures of AoA, proficiency, and ERP task accuracy are reported in Table 2.1. Results from the language background questionnaire confirmed that all L1 speakers reported learning French from birth, while L2 speakers learned French from a range of 0 – 16 years of age. Although one L2 speaker reported learning French from birth, they reported living in an English-speaking household in Montreal, and considered themselves an L2 speaker of French. L1 speakers' proficiency scores ranged from 63 – 100%, and L2 speakers' proficiency scores ranged from 32 – 91%. L1 speakers were significantly more accurate on all sentence types in the ERP task than were L2 speakers. There was a significant correlation between AoA and proficiency when both groups were combined (r = -.62, p < .001). However, this effect was not evident for the L2 speaker group alone (r = -.21, p = .380). L2 performance on the gender violation sentences (i.e., detecting the error in the gender violation sentence) ranged from 2.5 – 92.5% correct (M = 26%, SD = 20.12), indicating that some L2 speakers had difficulty detecting grammatical gender violations while performing well above chance on the rest of the task. Because some participants performed especially poorly on the gender violation detection task, additional analyses were run excluding those scoring below 25% accuracy on all violation conditions, as discussed further below.

2.3.2   Left Anterior Negativity

ERPs for control, gender and structure violations are shown in Figure 2.1; difference waveforms and topographic maps for the L1 and L2 groups are shown in Figure 2.2. To confirm that the grammatical gender and structure violations produced a LAN, we first examined the violation condition subtraction waves (i.e., gender – control and structure – control) within the 300 – 500 ms time window, across groups. A mixed ANOVA with violation, group, and ROI as fixed factors revealed a main effect of ROI type ($F(8, 304) = 4.08$, $p < .001$), no main effect of group ($F(1, 38) = .01$, $p = .907$, ns), no main effect of violation ($F(1, 38) = 1.19$, $p = .283$, ns), and no significant interactions. Post-hoc Bonferroni-corrected paired t-tests between violation types revealed that left frontal, right frontal, and left center ROI amplitudes differed significantly from posterior electrodes, with the most negative amplitudes in the left center ($M = -.91$ µV, $SD = 3.10$) and left frontal ($M = -.78$ µV, $SD = 3.23$) ROIs. These results suggest that as a whole, when not accounting for the variability in AoA or proficiency, our combined L1 and L2 sample showed a left anterior component in the LAN time window, and that this effect did not differ based on language status.
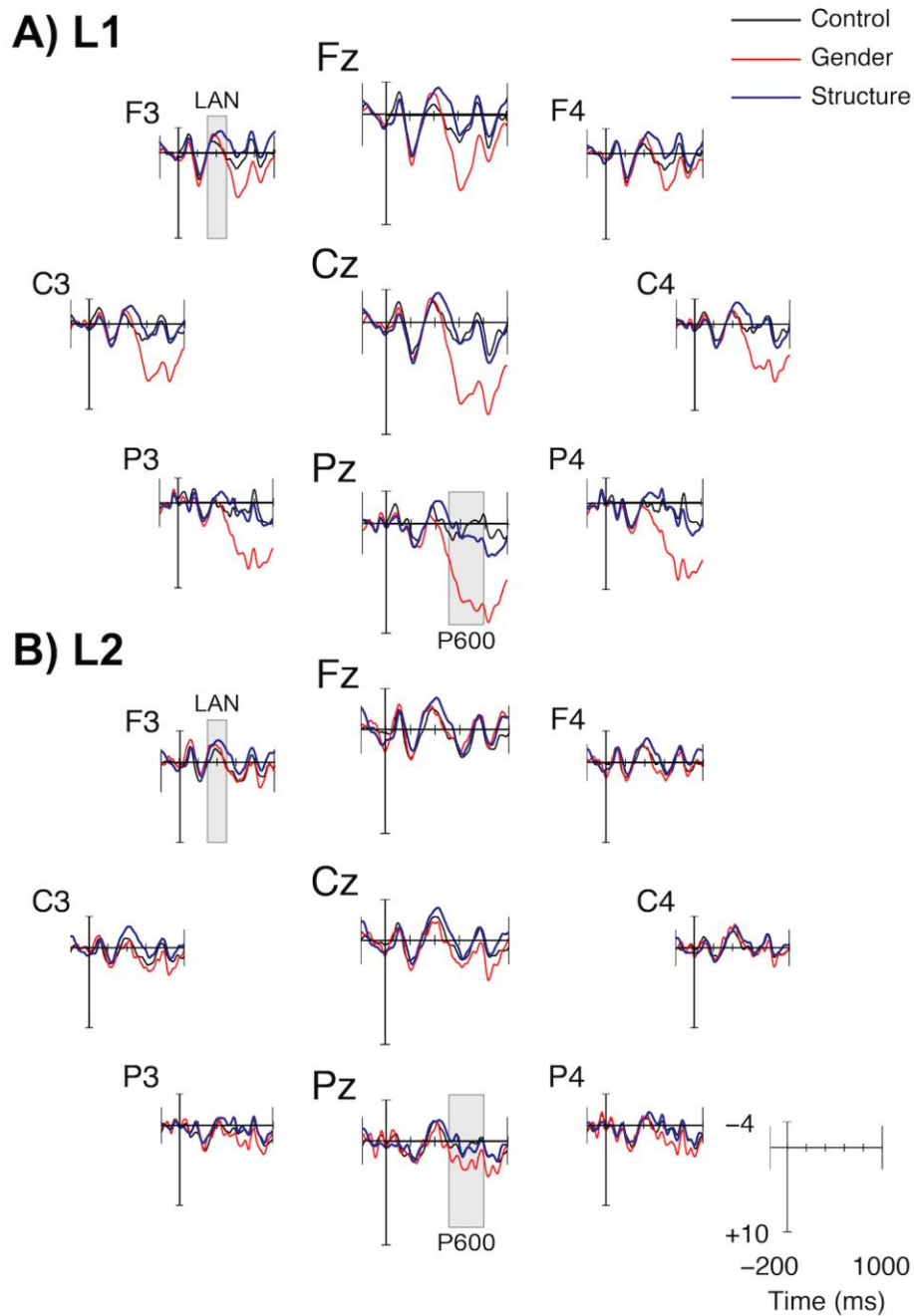
Figure 2.1. Group average ERPs for A) L1 French speakers and B) L2 French speakers for the control, gender violation, and structure violation sentences in the -200–1000 ms time window, between -4–10 µV. Negative is plotted upward.
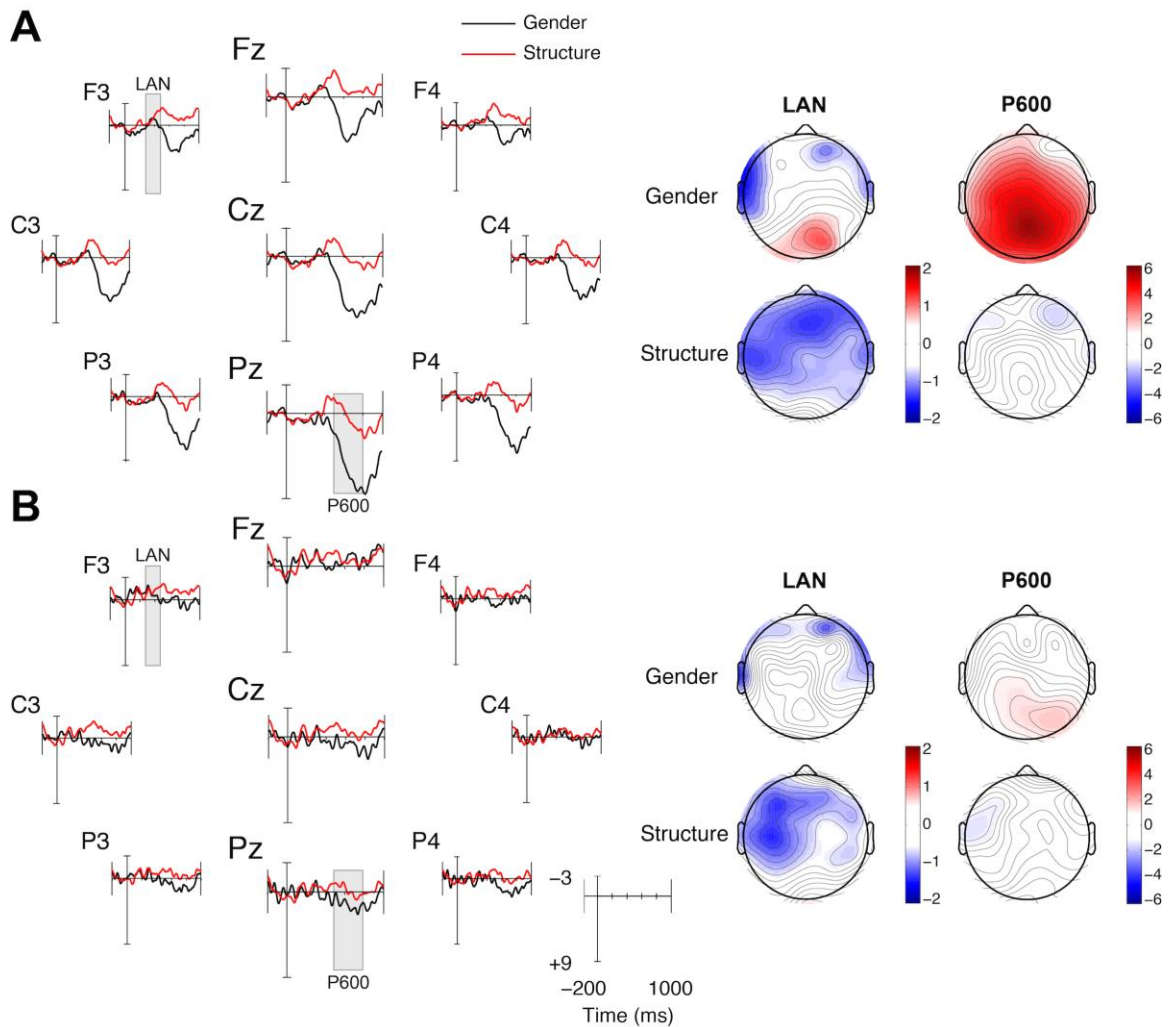
Figure 2.2. ERP differences waves and topographic plots for native and L2 French speakers. (A) ERP difference waves for L1 French speakers, computed as gender violation minus control in black and structure violation minus control in red. Negative is plotted upward. Topographic maps show the difference between gender violation minus control and structure violation minus control over LAN and P600 time windows for L1 French speakers. (B) ERP difference waves for L2 French speakers.

Next we examined whether AoA or proficiency might modulate the amplitude of the LAN in response to gender or structure violations, versus control sentences. A forward stepwise procedure to determine the best-fit LME model with group, proficiency, AoA, and ROI revealed that three factors, proficiency, AoA, and group, predicted LAN

amplitude, and the interactions are shown in Figure 2.3A. A significant violation type $\times$ proficiency interaction ($F(1,2536) = 38.13$ $p < .001$) was found and appears to be driven by structure violations, in that the amplitude of the LAN became more negative with increasing proficiency, while LAN amplitude in response to gender violations increased by .20 μV. A significant violation type $\times$ AoA interaction was also found ($F(1,2536) = 76.35, p < .001$). Unlike proficiency, the effect of AoA appears to be driven by gender violations rather than structure violations, with more negative LAN amplitudes for earlier AoAs. Finally, a significant violation type $\times$ group interaction was found ($F(1,2536) = 14.41, p < .001$), with L2s showing greater disparity between violation conditions.

In order to ascertain that the effect of AoA is not being driven by the L1 group whose AoA was uniformly zero, we repeated the same forward stepwise procedure with only individuals in the L2 group. Results were similar to the prior analysis: AoA was found to be the largest predictor as demonstrated by a significant violation type $\times$ AoA interaction ($F(1,1257) = 63.38, p < .001$; Figure 2.3B), followed by a violation type $\times$ proficiency interaction ($F(1,1257) = 31.25, p < .001$; Figure 2.3B). Again, the effect of AoA appears to be driven by gender violations, with more negative LAN amplitudes for earlier AoAs.
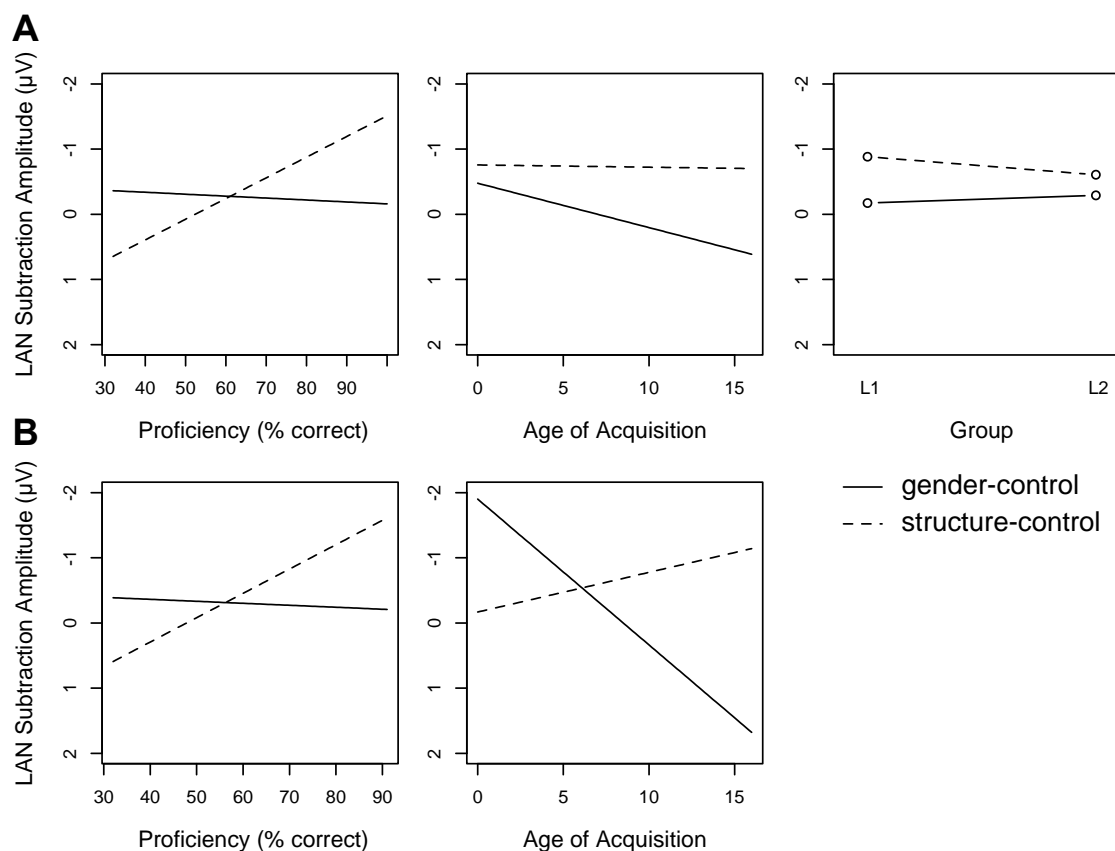
Figure 2.3. Proficiency, age of acquisition, and group interactions with sentence type in the LAN time window. (A) Violation type × Proficiency and violation type × AoA interactions across L1 and L2 French speakers. The *x*-axis is proficiency and AoA respectively, and the *y*-axis is mean LAN amplitude of the difference wave between 300-500 ms, with negative plotted up. The solid line is the gender violation minus control condition, and the dotted line is the structure violation minus control condition. B) Violation type × Proficiency and Violation type × AoA interactions across L2 French speakers only.

Because some participants performed especially poorly on the gender violation detection task, there was the concern that the signal-to-noise ratio for those individuals may have been extremely low due to the inclusion of very few accurate trials in their mean ERPs. This could in turn have artificially deflated the effect of grammaticality on observed ERP waveforms, which then could explain the individual differences effects observed above. To address this, data were reanalyzed including only individuals who

performed with 25% or greater accuracy on all conditions, with a total of 12 participants being removed, all from the L2 group. Results of the best-fit LME model with group, proficiency, AoA, and ROI did not differ from the initial LME LAN analysis. Thus, excluding participants with fewer correct trials yielded a similar pattern of significance as with the entire L2 sample.

These results indicate that both proficiency and AoA affect early syntactic integration, as indexed by LAN, however the type of syntax matters. AoA modulated LAN amplitude in response to gender violations, which are novel to L2 speakers, suggesting that learning the rule earlier leads to more native-like syntactic processing. Alternatively, proficiency modulated the LAN in response to structure violations, which are not unique to French, supporting the hypothesis that the structure errors are more egregious to higher proficiency speakers, while remaining unaffected by AoA.

2.3.3   P600

To confirm that violations were producing a P600, we examined the violation subtraction waves within the $500 - 800$ ms time window across groups. A mixed ANOVA with violation type, group, and ROI revealed a main effect of violation type ($F(1, 34) = 22.66$, $p < .001$) and a main effect of ROI ($F(8, 272) = 8.33$, $p < .001$). There was a significant violation type $\times$ group interaction ($F(1, 34) = 6.77$, $p = .014$), as well as a significant violation type $\times$ ROI interaction ($F(8, 272) = 3.97$, $p < .001$). Post-hoc Bonferroni-corrected Welch's t-tests revealed that groups differed in their response to gender violations, with L1s producing larger amplitudes to gender violations than L2s ($t(1114) = 11.53$, $p < .001$). Only the gender violations showed an effect of ROI, with the posterior left, center, and right, and the mid center ROIs differing from the frontal left and right ROIs ($p < .001$ in all comparisons). These results indicate that only L1 speakers produced a P600 to the gender violations, while no P600 was produced in either group to the structure violations.

We next examined whether AoA and/or proficiency modulated the P600 in response to gender and structure violations, beyond the group effect observed above. Forward stepwise LME analysis revealed that four factors predicted P600 subtraction

amplitude: proficiency, ROI, group, and AoA. Results revealed significant violation type × proficiency ($F(1, 2280) = 142.92$, $p < .001$), violation type × ROI ($F(1, 2280) = 4.22$, $p < .001$), violation type × group ($F(1, 2280) = 14.93$, $p < .001$), and violation type × AoA ($F(1, 2280) = 8.37$, $p < .001$) interactions. As can be seen in Figure 2.4 (see Figure 2.2 for topographic differences between violation types), the proficiency, group, and AoA interactions appear to be driven by gender violations. This suggests that proficiency, group, and AoA contributed independently to the P600 response. In contrast, amplitudes to structure violations were not modulated by these variables, suggesting that there is a difference between how proficiency, group, and AoA modulate grammatical gender violations and structure violations. As with the LAN, data were re-analyzed removing individuals scoring below 25% accuracy. Results showed a similar pattern as the previous P600 analysis.
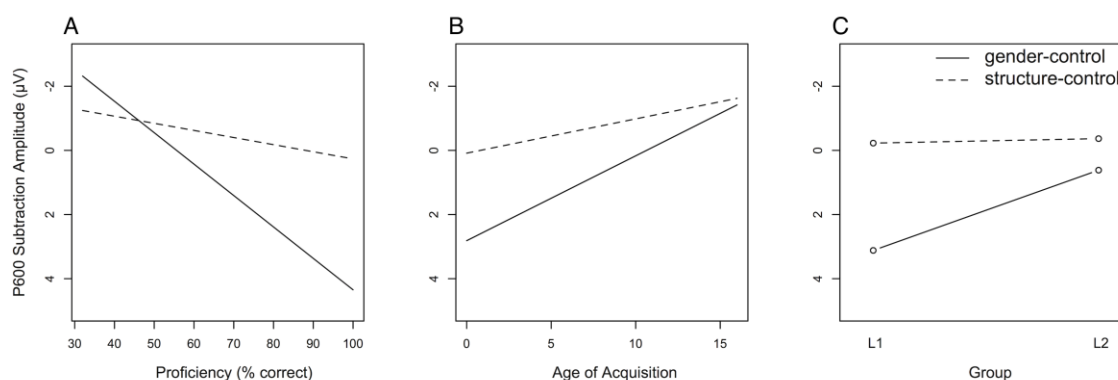
Figure 2.4. Proficiency, age of acquisition, and group interactions with sentence type in the P600 time window. (A) Violation type × Proficiency interaction across L1 and L2 French speakers. The *x*-axis is proficiency, and the *y*-axis is mean P600 amplitude of the difference wave between 500-800 ms, with negative plotted up. The solid line is the gender violation minus control condition, and the dotted line is the structure violation – control condition. (B) Violation type × AoA interaction across L1 and L2 French speakers. (C) Violation type × Group interaction.

2.4   Discussion

The present study used event-related potentials to examine the effects of AoA and proficiency on grammatical gender processing in second language speakers whose first language does not possess a gender system. We measured brain responses in native French speakers and L2 French speakers as they read control sentences and sentences containing syntactic violations that evoked the LAN and P600 components. Our unique sample of participants allowed us to treat both proficiency and AoA as continuous variables, providing a more complete description of how both variables predict grammatical gender processing. Results indicated that, at what we would argue to be first-pass stages of grammatical processing, AoA predicted LAN amplitude to gender but not structure violations, while proficiency predicted LAN amplitude to structure but not gender violations. L2 speakers also showed a greater disparity between LAN responses to gender and structure violations. However, at later stages of grammatical processing, proficiency, group, and AoA each independently predict P600 amplitude to gender violations, while there was no P600 elicited to structure violations.

2.4.1   Left Anterior Negativity

When only considering group membership, a LAN was elicited to both structure violations and gender violations in both groups. However, when including group membership, proficiency, and AoA in the model, proficiency predicted an increase in amplitude to structure violations, while AoA predicted a decrease in amplitude to gender violations. The LAN is thought to represent early syntactic integration or first-pass grammatical processing reflecting detection of a syntactic violation (Bornkessel & Schlesewsky, 2006; Friederici, 2002; Friederici et al., 1993; Rösler et al., 1993). These results thus suggest that, as AoA increases, individuals increasingly fail to exhibit this early-stage marker of grammatical gender processing. This effect holds despite participants' overt detection of errors – as marked by affirmative behavioural response. Moreover, this effect also holds when controlling for second-language proficiency level as measured offline by a standardized measure. This finding is supported by the existing literature, in which late AoA learners were found to have reduced or absent neural

markers of early syntactic processing when compared to native speakers or early L2 learners (Pakulak & Neville, 2011; Wartenburger et al., 2003; Yan, Zhang, Xu, Chen & Wang, 2016). The present results confirm that this effect does owe to age-dependent effects and are not strictly due to these individuals' overall proficiency in their second language.

In the present study proficiency did not predict LAN amplitude in response to gender agreement violations, with only AoA explaining significant variance in amplitude. Thus, it is possible that changes in LAN amplitude previously attributed to proficiency may in fact be due to AoA, which is often highly correlated with proficiency. Proficiency explained significant variance in LAN amplitude to structure violations, with larger LANs as proficiency increased in the combined L1 and L2 sample. This positive relationship suggests that with regards to structure violations, increased proficiency predicts stronger early syntactic processing in both L1 and L2 speakers. These results replicate research showing that higher proficiency monolinguals show greater LAN amplitude to syntactic errors than low proficiency monolinguals (Pakulak & Neville, 2010), suggesting that proficiency is a major contributor to syntactic processing in both L1 and L2.

The difference in contributing factors to structure violation and gender violation processing indicates that L2 processing of these two forms of syntactic processing relies on dissociable neurocognitive mechanisms. The present results indicate that early syntactic integration of structure errors to the rest of the sentence depends on proficiency; the more proficient, the more difficult it is to integrate the error into the sentence, indexed by larger LAN responses. This is in contrast to gender violations, which are more sensitive to AoA than to proficiency, with early integration processes becoming less involved as AoA increases, indexed by decreasing LAN amplitude as AoA increases.

AoA is thought to affect syntactic processing more than proficiency (Pakulak & Neville, 2011; Weber-Fox & Neville, 1996; Wartenburger et al., 2003); proficiency has also been argued to affect semantic processing more than AoA (Weber-Fox et al., 2003; Wartenburger et al., 2003). Given the lack of P600 to structure violations and the

negativity between 300-500 ms, it could be proposed that the evoked effect is in fact an N400 rather than a LAN. This would imply that participants were treating structure violations as semantic violations rather than syntactic violations, and producing an N400, and would support the hypothesis that proficiency predicts semantic processing. Indeed, recently some have suggested that the LAN may in fact be an N400, which has a skewed topography due to the following P600 (Tanner, 2014; Tanner & Van Hell, 2014). However, in the present study the LAN is not followed by a P600, and the topography of the evoked response to structure violations reflects that of the LAN, with the signal appearing greatest over left anterior electrodes. This is in contrast to the N400, which has a signal appearing greatest over midline centro-parietal electrodes. Additionally, Newman and colleagues (2012) found no relationship between proficiency in L2 and N400 amplitude. Thus, the evoked response appears characteristic of the LAN and it is not likely that the effect is in fact an N400. Although the LAN and P600 often occur together to form a LAN/P600 biphasic response (Gunter et al., 1996; Hahne & Friederici, 1999; Kim & Sikos, 2011; Molinaro et al., 2008), many studies have produced one effect without the other (Foucart & Frenck-Mestre, 2012; Friederici et al., 1993; Gillon-Dowens et al., 2011; Meulman et al., 2015; Schacht, Sommer, Shmuilovich, Martíenz & Martín-Loeches, 2014; Silva-Pereyra et al., 2012).

Despite the lack of a biphasic response in the structure violation condition, several conclusions can be drawn from the comparison to gender violations. We hypothesized that because syntactic structure is relevant to both English and French, knowledge of those syntactic rules in a specific language will be modulated by proficiency in that language. This is in contrast to AoA, which should not influence processing of structure violations because learning that rule (which is not novel) is not subject to neuroplastic effects (MacWhinney, 1987, 2005). Instead, AoA influences gender because the age at which L2 is learned determines the extent of neuroplastic effects, as the speaker has no foundation from L1 on which to build. At this early stage of syntactic processing, gender processing did not appear to be sensitive to proficiency. Thus, while it is possible for L2 speakers to acquire novel grammatical rules, this process is different to learning grammatical rules that are present in L1.

2.4.2   P600

When compared to the L2 learner group as a whole, only the L1 group yielded a significant P600 to gender violations, and neither group produced a P600 to structure violations. However, delving deeper into the L2 group data revealed a more nuanced set of results. When we included proficiency and AoA in the statistical model, proficiency, group, and AoA each contributed to P600 amplitude in response to gender violations, but not to structure violations. As predicted, P600 amplitude increased with increasing proficiency and decreased with increasing AoA. These results thus suggest that there are multiple contributing factors that influence late-stage syntactic processing. The P600 is thought to represent second-pass grammatical processing (Hahn & Friederici, 1999) or syntactic reanalysis (Kaan et al., 2000), suggesting that as a group, L1 speakers reanalyzed the gender violations more reliably than L2 speakers as a group. Interestingly, the results suggest that the proposed reanalysis stage indexed by the P600 is sensitive to the type of syntactic violation being induced. As a result, violations of word order yielded only a LAN and not a P600. Given this, it seems too simplistic to assume that any violation in syntactic structure invokes the same syntactic error detection and/or reanalysis mechanisms, and that this process may in fact be multifactorial. Indeed, the present findings lend further support to dissociable syntactic processes characterized by the LAN and P600 (Molinaro et al., 2014).

L2 speakers as a group did not produce a significant P600 in response to gender violations; however, further inspection revealed that this reflected the large variability in proficiency and AoA in our sample. Closer inspection revealed that both these factors predicted significant variance in P600 amplitude such that higher proficiency and earlier AoA both yielded larger P600 violation effects. That said, group still contributed significant variance in our analysis of the combined L1 and L2 samples. This supports the view that regardless of other factors, this aspect of L2 language processing is still qualitatively different to L1 language processing. This is concordant with the view that even early L2 learners show differences in neural markers of syntactic processing (Hernandez & Li, 2007; Kotz, 2009; Weber-Fox & Neville, 1996).

2.4.3   Theoretical considerations

Different theories have been put forward to account for the differences observed in the AoA and proficiency literature. The declarative/procedural model (Ullman, 2001) suggests that the processing of semantics in both L1 and L2 relies on declarative memory, and has shared neural bases. In contrast, syntactic processing in L1 and initial L2 learning are proposed to have different neural bases. In L1, grammar is subserved by procedural memory, which allows rules or sequences to be applied to semantic content. In L2 however, the procedural system is not initially available to the learner, who must instead rely on declarative memory processes for grammar processing. This reliance on declarative memory is proposed to be dependent on both L2 proficiency and AoA. At earlier AoAs, speakers are less dependent on declarative memory than at later AoAs, and as a speaker becomes more proficient in L2, the underlying neural processes regulating grammar shift to a more native-like state, relying more on procedural functions. This difference is proposed to account for why L2 learning is appreciably more difficult than L1 learning, even though it is still possible for some individuals to achieve high proficiency in their L2. Additionally, the declarative/procedural model highlights the interaction of AoA and proficiency.

In contrast, connectionist-based models of second language processing assume that L1 and L2 are processed by the same brain structures in similar fashions, albeit with L2 requiring greater processing resources within these regions (Abutalebi, 2008; Indefrey, 2006). For instance, Indefrey (2006) has suggested that L1 and L2 rely on similar neurocognitive mechanisms, but lower processing efficiency in late-learning or low-proficiency L2 speakers leads to different patterns of activity. As L2 speakers become more proficient in their L2, their neural language function becomes more efficient, leading to more native-like processing. Similarly, Abutalebi (2008) has proposed that L2 grammar and vocabulary are acquired through structures similar to those in L1. The author suggested that the neural representation of language processing is more extended in L2 speakers, in part due to competition between L1 and L2, but also that, as they become more proficient, processing becomes more automatic and native-like.

Similarly, MacWhinney's Unified Competition Model (2005) posits that, although weakened in L2 acquisition, L1 and L2 acquisition share core learning mechanisms. Linguistic similarity between L1 and L2 is known to affect L2 processing (Jeong et al., 2007; Sabourin et al., 2006; Sabourin & Stowe, 2008), and the Competition Model states that both in semantics and syntax, any item that can transfer from L1 and L2, will. However, transfer is most effective earlier in life, when the brain is more plastic.

The effect of AoA, proficiency, and group (i.e., native or L2 speaker) on syntactic processing markers is consistent with the declarative/procedural model of L1 and L2 syntactic processing. Although both the declarative/procedural model and connectionist models suggest an effect of proficiency, we observed this effect a) on structure violations, which are similar in L1 and L2, thus would not be affected by AoA or group, and b) on later-stage processing of gender violations, suggesting that earlier, automatic syntactic processing depends on different neural mechanisms between L1 and L2 speakers. Thus, while rules that are similar between L1 and L2 may share neural bases, AoA largely predicts how novel syntactic rules are processed. The Competition model predicts an effect of AoA on syntactic processing, however we also observed an effect of proficiency and group independently of AoA. Additionally, it has been argued that the early age of typical L1 acquisition can itself explain L2 learning outcomes, regardless of L2 AoA (Mayberry & Lock, 2003); however, while the present study did not examine L1 AoA, we have demonstrated clear influences of both L2 AoA and proficiency on grammatical processing in L2.

Finally, there remain potential confounds with respect to the differences in response to the phrase structure and gender violations. First, phrase structure and gender violations are two different forms of grammatical violation, with phrase structure being purely syntactic and gender violations being morphological. Phrase structure violations were used due to their similarity across English and French. Second, in addition to their cross-language similarity, phrase structure violations may simply be more disruptive and easy to learn than gender violations, resulting in differences in processing. Finally, gender violations were always indexed to nouns; in contrast, structure violations were while usually indexed by a noun, sometimes occurred relative to other types of words

instead. This raises the concern that ERP differences between the two violation types might reflect the type of word they occurred in rather than a morphosyntactic process. That said, this explanation seems unlikely give that previous research has identified the LAN/P600 complex in response to both phrase structure violations and gender violations (Barber & Carreiras, 2005; Newman et al., 2007; but see Steinhauer & Drury, 2012). Additionally, number and gender violations have been compared previously in Chinese-Spanish learners, with no difference being found between the two forms of violation (Gillon Dowens et al., 2011). However, the different results between the two violation conditions cannot be solely assigned to cross-language similarities/dissimilarities, and future research should seek to disentangle these potential confounds.

In conclusion, the present study investigated how individual differences in L2 proficiency and AoA (AoA) influenced ERP markers of both novel and similar grammatical processing. We found that while AoA predicted LAN amplitude in response to novel grammatical rules, AoA, proficiency, and group membership (L1 vs. L2) predicted P600 amplitude. In contrast, proficiency predicted LAN amplitude to grammatical rules that are similar across languages, with no P600 effect. The results of this study highlight the importance of examining individual differences in understanding neural markers of L2 language processing. It similarly highlights the utility of considering similarities and differences between L1 and L2 in this respect. Different effects of AoA and proficiency between gender and structure violations indicate that while it is possible for L2 speakers to acquire novel grammatical rules, this process is different to learning grammatical rules that are present in L1. Additionally, while second language speakers can approach what looks like native-like processing, the fact that they are L2 speakers still affects syntactic resolution independently of both proficiency and AoA, suggesting differing neural mechanisms for syntactic processing of L1 and L2.

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3 Representational dissimilarity of first and second languages in the bilingual brain

3.1 Introduction

Much of the current bilingualism literature focuses on the coactivation of a bilingual's two languages (Pyers and Emmorey, 2008; Spalek et al., 2014; Starreveld et al., 2014; Goldrick et al., 2016). Current thinking holds that bilingual speakers coactivate their two languages during speech, and that they maintain similar, overlapping representations for both. Additionally, past neuroimaging research has provided much evidence that a second language (L2) is processed similarly to the speaker's first language (L1; Perani et al., 2003; Indefrey, 2006; Wang et al., 2011; Cao et al., 2013; Sun et al., 2015). Even when L1-L2 differences exist, such as more extensive activity in L2 (Lucas et al., 2004; Nichols and Joanisse, 2016), there remains extensive overlap (Indefrey, 2006). This suggests that similar underlying language networks are engaged regardless of which language is being used. The concept of language coactivation in bilinguals is widely accepted, as is that of a single, integrated lexicon (see van Heuven & Dijkstra, 2010, for a review). While neuroimaging provides much support for an integrated lexicon through activation of similar structures, the separation of activity within the shared L1/L2 brain areas may provide evidence for some degree of distinction between L1 and L2 lexicons.

Despite L1 and L2 sharing a network of structures, bilinguals are still able to keep separate their two languages, indicating that there is some degree of neurocognitive differentiation of the two languages. Yet, whereas traditional univariate contrasts are useful for indicating which brain areas differ in level of activation between L1 and L2, they cannot tell us how languages are being represented in those areas. While we know that there is extensive overlap in brain areas that represent L1 and L2 (Chee et al., 1999a; Perani et al., 2003; Indefrey, 2006; Wang et al., 2011), how the languages are represented may vary. That is, regions coding for language-specific information, such as spoken codes (e.g., left superior temporal gyrus and left inferior frontal gyrus) are likely to represent each language differently. In contrast, regions involved in executive and attentional control (e.g., dorsolateral prefrontal cortex and insula) are likely to show less

differentiation in how each language is represented as the function of these regions should not differ qualitatively from one language to another.

Representational Similarity Analysis (RSA) is an fMRI analysis technique relying on reproducible spatial patterns of activity that correlate with distinct experimental conditions (Kriegeskorte et al., 2008). RSA has been used to reveal differences between conditions within individual brain regions that were previously undetectable using standard univariate methods; it reveals cortical patterns sensitive to stimulus patterns even when there is no apparent difference in degree of activation (Connolly et al., 2012; Joanisse and DeSouza, 2014; Ejaz et al., 2015; Fabbri et al., 2016). RSA may be particularly relevant to describing the bilingual lexicon, as it has the potential to identify differences between languages that were previously thought to not exist. RSA allows us to examine possible language-processing differences in areas that are assumed to be engaged similarly for both languages, suggesting that they are representing L1 and L2 differently.

3.1.1   Rationale for the Present Study

The present study examined whether brain areas involved in both L1 and L2 representationally distinguish the two languages. English-Mandarin bilingual adults performed a lexico-semantic recognition task in each language. We then examined which brain regions would show reliably different patterns of activity for either language. We predicted that this should hold for language-related perisylvian brain regions classically implicated in core language processes. In contrast, areas involved in domain general cognitive processes, such as executive function, were not expected to show language-selective patterns even if they differ between languages in their degree of engagement in univariate contrasts. Additionally, because research has suggested fundamental differences between L1 and L2 processing (Newman et al., 2012a), we investigated whether areas that differentiated languages in representational patterns might in fact represent one language more reliably than the other.

3.2   Methods

3.2.1   Participants

Twenty-six (8 female) neurologically healthy right-handed native speakers of English were recruited via posters and word of mouth in Beijing, China. Human subjects were recruited at Beijing Normal University. All participants were second-language learners of Mandarin, ages 20-37 ($M = 24.54$, $SD = 4.78$), and had begun learning Mandarin between the ages of 13-28 years ($M = 20.31$, $SD = 4.70$).

3.2.2   Behavioural materials

L1 English and L2 Mandarin proficiency levels were assessed prior to scanning using a subset of 48 questions from the Test of English as a Second Language (ETS, Princeton, NJ) and 48 questions from the Hanyu Shuiping Kaoshi (HSK Centre, Beijing, China), respectively. Both tests consisted of three sections, grammar, reading comprehension, and vocabulary, which were combined to give a final mark out of 48 for each language, representing overall proficiency in these three domains.

Age of acquisition was obtained by self-report, defined as the age at which individuals first began learning Mandarin. To verify handedness, participants completed an abridged version of the Edinburgh Handedness Inventory (Oldfield, 1971). Behavioural measures, letters of information, informed consent and task instructions were administered in English, aside from the Mandarin proficiency test which was administered in Mandarin.

3.2.3   fMRI Task

Participants completed a picture-word matching task during scanning, in alternating runs of English and Mandarin. Pictures were presented via LCD projector to the center of a screen mounted at the head of the scanner bore, which was viewed through a mirror placed above the head coil. At the same time, a word was played binaurally through insert earphones (Sensimetrics Corporation, Malden, MA). Participants were required to indicate as quickly as possible with a button press whether the picture and word matched. Each picture was visible for 2.5 s. Stimulus presentation and response

recording was controlled with E-Prime software (Psychology Software Tools, Inc., Sharpsburg, PA) and a Windows laptop.

The scanning session was divided into 8 runs of 20 trials each for a total of 160 trials (80 in each language). A short break was provided between each 3.5-minute scanning run. Each image appeared twice during the experiment, once in a matching pair and once in a semantically unrelated mismatching pair. Four English runs alternated with four Mandarin runs, with starting language counterbalanced. Each run began with an image reminding participants of which buttons to respond with, and the language in which the next run would be performed. Each trial was 2.5 s in duration, with inter-trial interval jittered between 2.5 and 12.5 s in 2.5 s increments, to optimize the deconvolution of the blood oxygen level dependent signal. They viewed a fixation crosshair between trials.

Stimulus words consisted of 40 common single-word concepts with the constraint that they are expressed as single two-syllable words in both English and Mandarin, and have frequencies greater than 40 per million in both languages (English: CELEX Lexical Database, Baayen, Piepenbrock, & Gulikers, 1995; Mandarin: SUBTLEX-CH, Cai & Brysbaert, 2010). In a separate pilot study involving different participants, we asked groups of native speakers of English or Mandarin to rate the imageability and familiarity of the stimulus words, as well as the correspondence of the pictures to target words. Images were retrieved by performing a Google image search of each word in English. Both groups showed equally high ratings on all three sets of measures; no differences were observed for ratings of familiarity and picture/word correspondence, although imageability was rated higher for Mandarin words than English words (t(39) = -2.89, p = .004).

3.2.4   fMRI acquisition and processing

Imaging was conducted on a Siemens Magnetom TIM Trio whole-body 3 Tesla scanner with a 32-channel head coil. T2*-weighted functional scans were acquired in the transverse plane with 45 slices per volume (TR = 2.5 s; TE = 38 ms; flip angle = 80°; FOV = 192 x 192 mm; voxel size 3x3x3 mm) using an iPAT parallel acquisition sequence (generalized auto-calibrating partially parallel acquisition [GRAPPA];

acceleration factor = 2), providing full coverage of the cerebrum and the superior portion of the cerebellum. A total of 576 functional scans were acquired for each participant over 8 runs (3.5 min per run). After the final functional run, a whole-head high-resolution 3D anatomical scan was acquired in the sagittal plane, using a 3D pulse sequence weighted for T1 contrast (MPRAGE; TR = 2.3 s; TE = 2.98 ms; FOV = 256 x 256 mm; voxel size = 1 mm^3; 176 slices; GRAPPA acceleration factor = 2).

Data preprocessing was performed using the AFNI software package (Cox, 1996, build date December 9, 2015). Functional scans were first de-obliqued (transformed to the same cardinal orientation as the anatomical scan, AFNI *3dWarp*), then motion corrected by registering each volume to the last functional volume of the session, which was acquired immediately preceding the anatomical scan, using a 3d rigid body transformation (AFNI *3dvolreg*). Outlier volumes caused by hardware artifacts were identified as ones significantly deviating from average image intensity using AFNI *3dToutcount*, and subsequently removed from statistical analyses using the CENSORTR option in AFNI *3dDeconvolve*.

Single-subject statistical maps were formed using a general linear model (GLM) with the following four predictor functions: one each for even and odd trials of English runs, and one each for even and odd Mandarin runs. Only correct trials were included in the analysis, with accuracy ranging from 81.25% to 100% correct on the English task, and ranging from 61.25% to 96.25% correct on the Mandarin task. A 4 mm FWHM Gaussian spatial filter was then applied (AFNI *3dmerge*). In order to perform univariate contrasts, each participant's GLM was then skull-stripped and transformed to stereotaxic space of Talairach and Tournoux (1988) via an automatic registration procedure (12-parameter affine transform, least-squares cost function; AFNI @*auto_tlrc*). Finally, paired samples t-statistic maps were obtained for differences in activation levels between L1 and L2 trials (AFNI *3dttest++*), across the combined even and odd runs.

Searchlight RSA was then performed to identify regions in which the representations of L1 and L2 were reliably different, regardless of groupwise differences in activation levels. The search space for the analysis was constrained to regions generally involved in word recognition tasks such as the one used here. This was determined using the Neurosynth meta-analysis tool (Yarkoni et al., 2011), using the term

"word recognition" to produce a probability map of brain regions likely to evoke activity on this type of task across 74 prior studies (8 Chinese) listing this keyword. The resulting brain map was then transformed to the native space of each participant and served as a functional mask, which restricted analyses to those regions generally considered to be involved in word recognition, listed in Table 3.1. To perform RSA, a split-half correlation searchlight was performed within the CoSMoMVPA Matlab toolbox, using a search sphere radius of 3 voxels (Oosterhof et al., 2016). Within each searchlight sphere Pearson correlations were performed for activity patterns between even and odd runs, within-language (English-English and Mandarin-Mandarin) and between-language (English-Mandarin), yielding a 2×2 similarity matrix for each individual. Next, the degree of dissimilarity of between-language vs. within-language patterns (on-diagonal vs. off-diagonal) was computed using a pairwise t-test based on the difference of Fisher-transformed mean correlations for matching and non-matching conditions (Haxby et al., 2001). Significant differences in an area within the searchlight sphere indicated this region differentially encodes L1 and L2. The center of the searchlight was then moved to the next location of the search space, and the statistical analysis was repeated, ultimately yielding a statistical map of all voxels falling within the "word recognition" search space. Analyses were performed using de-meaned coefficient maps in each individual's native space. These searchlight maps were then transformed into standard Talairach space, and a group statistic was created via a one-sample t-test, which identified voxels showing significantly greater representational similarity within-language than between-languages.

Correction for multiple comparisons at $p < .01$ was achieved for the group univariate statistical map by setting a minimum cluster size of 459 mm^3, obtained using a 100,000 iteration Monte Carlo simulation (AFNI *3dClustSim*; voxel-wise $\square < .01$, accounting for observed mean spatial blurring in each dimension using AFNI *3dFWHM*). Correction for multiple comparisons at $p < .01$ was achieved for the group RSA searchlight statistical map by setting a minimum cluster size of 324 1 mm^3 voxels, obtained using a 10,000 iteration Monte Carlo simulation (AFNI *3dClustSim*) within a reduced search space corresponding to the 'word recognition' mask (voxelwise $\square < 02$, again accounting for observed mean spatial blurring in each dimension). Post-hoc t-tests

comparing the degree of within-language representation were Bonferroni corrected for two comparisons at $\square < .05$.

Table 3.1. Clusters of activation included in the "word recognition" meta-analysis, with associated terms, retrieved from NeuroSynth.

	Region	Talairach coordinates				NeuroSynth Association Word
		x	y	z	Size (mm^3)	
L	Inferior frontal gyrus	-45	17	13	16,408	Comprehension
L	Medial frontal gyrus	-0	17	46	3,256	Task
R	Middle frontal gyrus	45	14	26	3,184	Demands
R	Inferior frontal gyrus	38	23	-4	2,512	Demands
L	Middle temporal gyrus	-49	-50	-7	13,808	Word
R	Middle temporal gyrus	48	-38	2	680	Spoken
R	Middle temporal gyrus	48	-68	29	368	Default
L	Superior parietal lobe	-28	-59	47	2,336	Arithmetic
L	Inferior parietal lobe	-47	-35	46	368	Arithmetic
R	Superior parietal lobe	31	-56	47	800	Calculation
R	Middle occipital gyrus	47	-63	-10	776	Objects
R	Cingulate gyrus	4	25	30	704	Pain

3.3 Results

3.3.1 Behavioural

Analyses of the proficiency test data acquired prior to scanning indicated that L2 proficiency was significantly lower than L1 proficiency ($t(25) = -16.50$, $p < .001$). Participants responded faster on English trials than Mandarin trials ($M = 1.18$ s, $SD = 1.93$, $M = 1.61$ s, $SD = 2.40$, respectively; $t(25) = -15.17$, $p < .001$) and were more accurate on English trials than Mandarin trials ($M = 94.50\%$, $SD = 4.49$, $M = 83.54\%$,

SD = 9.94; *t*(25) = 6.57, *p* < .001).

3.3.2   Univariate analysis

Results of the L2-L1 contrast are shown in Figure 3.1 and Table 3.2. At the group level, L2 Mandarin produced greater activation than L1 English across multiple language-related brain regions including the bilateral superior temporal gyri (STG), left prefrontal regions, right primary motor area, and bilateral caudate. L1 English did not produce greater activation than L2 Mandarin in any areas.

Table 3.2. Clusters of significant activation in L2-L1 contrast at a voxel-wise alpha of *p* < .01, and a corrected *p*-value of p < .01.

Contrast		Region	Talairach coordinates			
			x	y	z	Size (mm^3)
L2 Mandarin > L1 English	L	Superior frontal gyrus	-14	41	43	780
	L	Precentral gyrus	-54	0	40	1,410
	R	Precentral gyrus	45	-6	44	4,914
	L	Transverse temporal gyrus	-47	-19	13	31,287
	R	Superior temporal gyrus	50	-28	14	17,150
	L	Inferior parietal lobe	-42	-37	40	5,088
	L	Precuneus	-32	-65	40	504
	L	Precuneus	-4	-72	51	660
	R	Precuneus	1	-36	46	865
	L	Cuneus	-10	-69	13	811
	L	Lentiform nucleus	-20	13	10	5,643
	R	Anterior cingulate	0	44	6	582
	R	Caudate	7	10	6	2,566
	R	Cingulate gyrus	5	-7	47	8,419
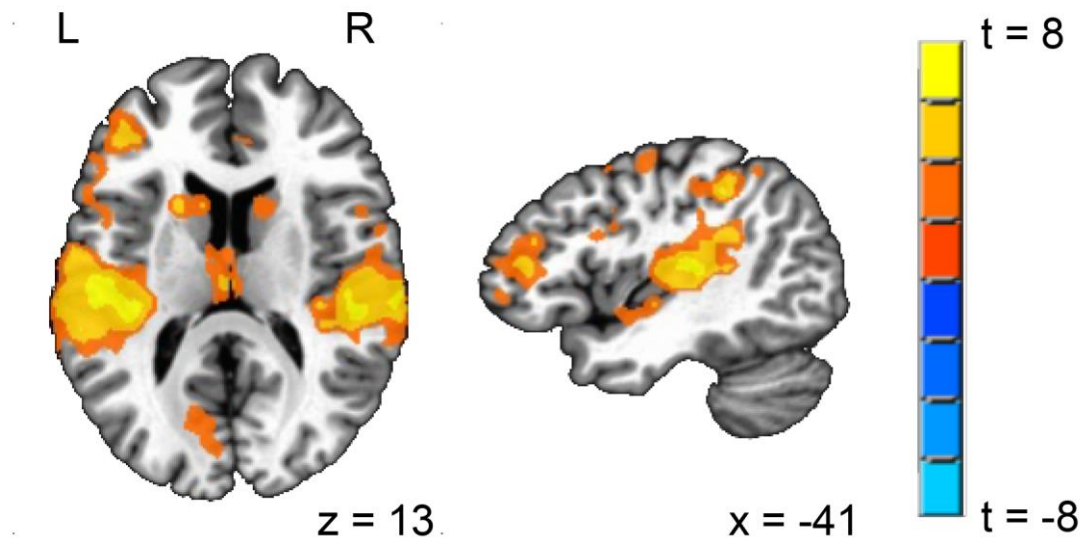
Figure 3.1. Regions showing differences between L1 English and L2 Mandarin, at a statistical threshold of *t* = 2.80, *p* = .01. Positive values indicate L2 > L1 activation. Statistical maps overlaid on the N27 atlas brain. L = left, R = right.

3.3.3   Multivariate analysis

RSA measured the similarity of voxel activation patterns for English and Mandarin word recognition within the "word recognition" functional map retrieved from Neurosynth. Data were de-meaned prior to RSA analysis in order to negate the possibility that differences in the degree of region-wise activation could affect the pattern of representation. Both the search space and results of the searchlight analysis are depicted in Figure 3.2, and correlation matrices are visualized in Figure 3.3. Within each matrix in Figure 3.3, the Fisher-transformed correlation coefficient between each condition is plotted, with the shading of each square denoting the degree of similarity; statistical analyses then contrasted the correlation coefficients to assess whether representational similarity within each ROI was different for the conditions of interest.
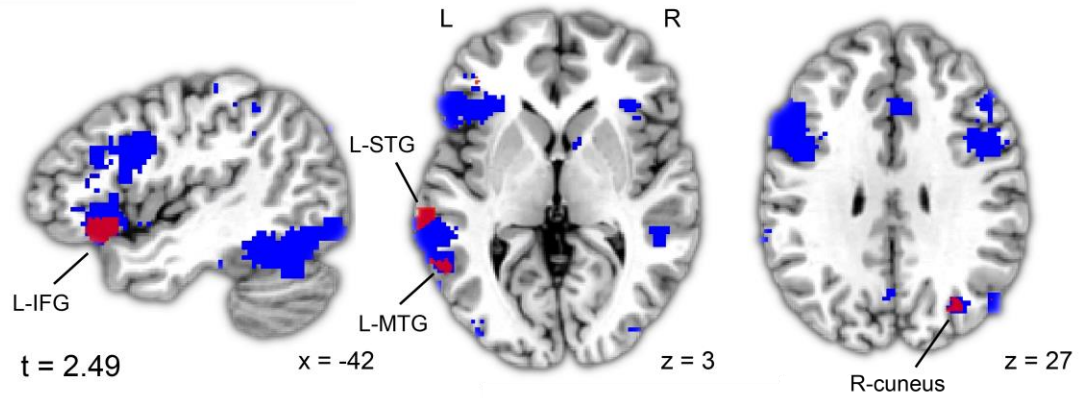
Figure 3.2. Results of the searchlight analysis (in red) superimposed on the "word recognition" meta-analysis brain mask (in blue), at a statistical threshold of $t = 2.49$, $p = .02$. Statistical maps overlaid on the TT-N27 atlas brain (Talairach & Tournoux, 1988). L = left, R = right.
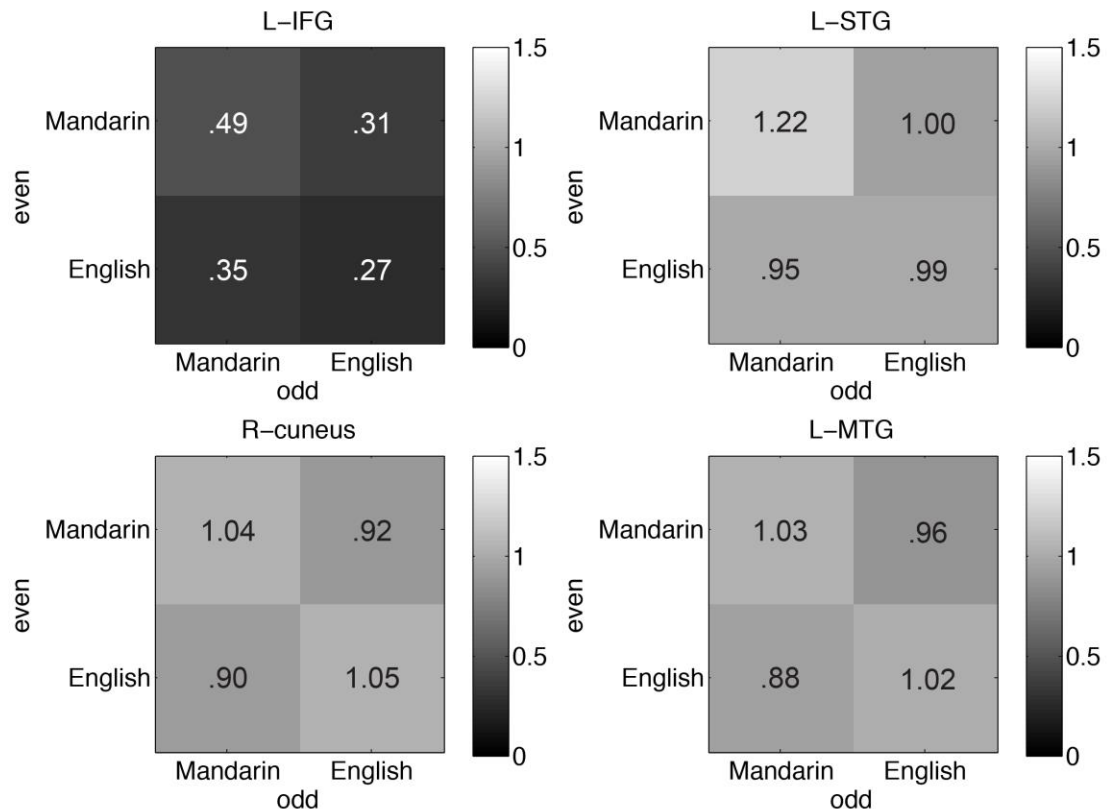
Figure 3.3. Mean correlation of activity patterns between even (rows) and odd (columns) runs of the Mandarin and English tasks, at each region of interest.

**Within-language correlations correspond to the diagonal of the matrix, while between-category correlations correspond to the off-diagonal values. Higher similarity is depicted by higher correlation and lighter shading. Indicated values represent Fisher-transformed correlation coefficients. Data were de-meaned prior to performing RSA to ensure differences in representation were not influenced by differences in activation levels.**

Results revealed separate activity patterns in four areas and are summarized in Table 3.3: left inferior frontal gyrus (IFG), left STG, right precuneus, and left middle temporal gyrus (MTG). This is demonstrated by stronger correlations within each matrix for conditions along the diagonal (Mandarin-Mandarin and English-English) compared to the off-diagonal (Mandarin-English) in all four areas.

Table 3.3. Clusters showing significant on-off diagonal dissimilarity at voxelwise *p* < .02, and a 1-sided corrected *p*-value of p < .01

	Region	Talairach coordinates			
		x	y	z	Size (mm^3)
L	Inferior frontal gyrus	-37	24	-14	1177
L	Superior temporal gyrus	-59	-21	-3	957
L	Middle temporal gyrus	-49	-53	-1	359
R	Precuneus	25	-68	30	596

Note.   Coordinates denote the location of peak statistical value. L/R = left/right.

On-off diagonal dissimilarities in two of the ROIs, the left IFG and the left STG, appeared to be driven by the Mandarin-Mandarin correlation. This is shown in Figure 3.3 by the higher Fisher-transformed correlation coefficient in the Mandarin-Mandarin cell of each matrix. To determine whether similarity was stronger for Mandarin than English in each region, we extracted the within language Fisher-transformed correlation coefficients for each participant. We then compared correlation coefficients in each on-diagonal cell (i.e., Mandarin-Mandarin and English-English) using a one-tailed paired t-test. In the left IFG, coefficients for the Mandarin-Mandarin correlation were significantly higher than

those of the English-English correlation (t(25) = 2.46, *p(corr)* = .021; we also noted a similar but non-significant effect in the left STG, where differences in coefficients for the Mandarin-Mandarin and English-English correlations just missed significance following correction for multiple comparisons; t(25) = 2.04, *p(corr)* = .052). The difference in the degree of within-language representation similarity would suggest that at least some left perisylvian language subregions maintain distinct representations for L2 Mandarin, but not L1 English. Finally, in order to determine whether AoA or proficiency predict the degree of within-language representation similarity, subject-wise correlation coefficients for the Mandarin-Mandarin and English-English correlations were extracted. Neither AoA nor proficiency correlated with within-language correlations (*p* > .05 for all correlations).

RSA did not reveal evidence for differentiation with the remaining areas of the word recognition network, listed in Table 3.1, as marked by a failure to find a significant difference in similarity of activation patterns within-language vs. between-language. These results suggest that these areas of the word recognition network are generally not sensitive to differences between languages in bilinguals.

3.4 Discussion

The present study investigated the hypothesis that bilinguals maintain similar, overlapping lexical representations for both their languages. We provide evidence of a neural mechanism for both coactivation of languages and an integrated lexicon, while allowing for the speaker to function in one language without intrusion of the other language. Using a word recognition task, we found both similarity and dissimilarity in representation of bilinguals' two languages throughout the bilingual word recognition network. Four regions differed in their representation of English and Mandarin: the left IFG, left STG, left MTG, and the right precuneus. These differences in representation were not due to differences in activation level. This is the first study to show differentiation in the representation of bilinguals' two languages in areas that were thought to be involved in language processing for both languages, and that did not distinguish between languages at the univariate level, i.e., in level of activation (Perani et al., 2003; Indefrey, 2006; Wang et al., 2011; Cao et al., 2013; Sun et al., 2015). These

results extend behavioural and ERP findings that bilinguals have a single, integrated lexicon (Midgley et al., 2008; van Heuven and Dijkstra, 2010; Jouravlev et al., 2014; Ando et al., 2015), yet are able to inhibit one language while speaking the other. While prior meta-analyses and reviews have argued this on the basis of relative intensity of fMRI activity (Indefrey, 2006; van Heuven and Dijkstra, 2010), degree of activation cannot tell us about how each language is being represented. The results were not correlated with AoA or proficiency; as other fMRI analysis techniques have shown effects of individual differences, RSA may not be sensitive to these differences, and may be more sensitive to group-level effects.

Consistent with our hypotheses, areas involved in language-specific processing showed patterns of representation that differentiated languages, notably in the absence of differences in levels of activation. Search space was determined via meta-analysis a priori to include only areas involved in word recognition, therefore it is not possible to categorically assign functional roles to the areas that differentiated between English and Mandarin. However, the left MTG, IFG, and STG are all well studied areas of the language-processing network, and predictions can be made as to their potential contribution. The left MTG is involved in accessing word meaning (Scott and Johnsrude, 2003; Poeppel and Hickok, 2004; Hickok and Poeppel, 2007), and is thought to be part of a bilingual's integrated lexicon (Yokoyama et al., 2009; Isel et al., 2010). The left IFG is engaged in representing and planning articulatory codes for speech (Broca, 1865; Wise et al., 1999; Fedorenko et al., 2015). Indeed this differs significantly between English and Mandarin in that each language has phonological features that are not present in the other (e.g., tone in Mandarin, consonant clusters in English, among other factors). Finally, the left STG is well accepted as the locus of acoustic-phonetic coding of language, which again differs greatly between English and Mandarin (Scott and Johnsrude, 2003). The left IFG showed greater within-Mandarin correlations than within-English, suggesting that L2 Mandarin may require additional representational information. It may appear that these differences in representation simply reflect how Mandarin's articulatory code differs so greatly from those of English. However, if this effect simply reflected surface differences, for example tones in Mandarin and consonant clusters in English, both languages would be expected to show similar levels of representational similarity. The

present results instead suggest this is an L2 status driven effect supporting previous research showing fundamental L1 vs. L2 processing differences (Newman et al., 2012a). That is, adequately representing L2 may require additional information in the articulatory code. Additionally, the picture-word matching task may have prompted participants to subvocally activate the phonological form of the word depicted in the picture; this could require engaging the articulatory codes of the words, which differ between languages. Alternatively, because our participants were late Mandarin learners, the left IFG may also be representing subjective frequency differences between languages. Although words were matched on frequency and familiarity across languages in a separate study of native speakers, subjectively they may not be matched in late learners. This difference in subjective frequency may have been captured by the present methods, although other studies have shown that differences in word frequency manifest as differences in activation levels within the IFG, with low frequency words showing greater activation (Fiebach et al., 1999; De Bleser et al., 2003).

One notable result was that of representational similarity in the right precuneus, a cortical hub functionally connected to the visual processing network (Tomasi and Volkow, 2011). The separate representation in visual areas is especially interesting as participants in the present study saw the same images in each language; the manipulation here was only the language in which they heard the names of these objects. As a result, language-dependent differences in this region suggest that this reflects a top-down modulation of high-level visual processing by the auditory input. Although visual processing of the same images may appear to be a domain-general process, support for it being language-specific comes from the label-feedback hypothesis, which suggests that language modulates ongoing cognitive and perceptual processing (Lupyan, 2012). In line with this hypothesis, each language's verbal label for the paired image is affecting the perception of that image. Thus, while the image remains the same, the top-down influence of the language is producing separable representations in high-level visual areas, distinguishing between the visual perception of *table* vs. that of 桌子 (the Mandarin word for *table*).

By limiting the search space to the word recognition network we only identified areas that showed differences in representational patterns between languages. There remain a number of areas in the search space in which differences were not observed, either due to no existing differences, or to a lack of power in the present analysis. These areas included large sections of the right hemisphere, including frontal, temporal, and occipital gyri, in addition to sections of left IFG and STG, pre- and post-central gyri, and ventro-visual areas such as the lingual and fusiform gyri (Figure 3.2 and Table 3.1). While our meta-analysis reveals these areas are consistently implicated in word recognition processes, most are generally associated for domain-general processes; for example, the right IFG and MTG are involved in inhibitory control (Aron, 2007; Goghari and MacDonald, 2009; de Bruin et al., 2014), while the middle frontal gyrus and superior parietal lobe are involved in attention (Fox et al., 2006; Corbetta et al., 2008; Japee et al., 2015). The current methods suggest that the remaining regions in the word recognition network may not separate English and Mandarin, either in terms of absolute activity level or in terms of representational specificity, although differences in these areas may admittedly be simply too small to detect with the current methods.

Computational models of bilingual language representation such as the BIA+ model propose a division of the language subsystem and the attention subsystem (Dijkstra and van Heuven, 2002). That is, this view proposes that language-specific functions such as phonology and articulation are controlled within subsystems that are distinct from those that guided executive and attention constraints on bilingual language control. The model also proposes that there is an L1/L2 language "node", which determines which language will be accessed. While this model accounts for cross-language priming and interference (Jared and Szucs, 2002; Smits et al., 2006; Midgley et al., 2008; Jouravlev et al., 2014; Ando et al., 2015), the mechanism of the language node remains unclear at the neurobiological level. The observed independence of representation of English and Mandarin in language-specific regions such as the left STG, MTG, and IFG seem concordant with this view. It indicates that the distinction between languages may be present at the representational level, with word recognition in each language sharing neural resources but ultimately producing separable patterns of representation in the shared cortical areas. This is supported by predictions from other

theories of bilingual language processing such as Dual Coding Theory, which states that a bilingual's two languages possess separate semantic space (DCT; Paivio and Desrochers, 1980; Paivio and Lambert, 1981). In contrast, attention and executive control areas do not appear, at the present level of analysis, to represent L1 and L2 differently.

There have been numerous studies showing activation differences between L1 and L2, showing greater activation in language areas for one language vs. another (Chee et al., 2001; Ding et al., 2003; Perani et al., 2003), or showing additional areas recruited for L2 processing vs. L1 processing (Wang et al., 2011). These differences have largely been attributed to later acquisition of L2, differences in proficiency, or other external factors affecting how L2 was acquired (Chee et al., 2001; De Bleser et al., 2003; Indefrey, 2006). In contrast, matched bilinguals tend to show overlapping activity in language regions, with little or no differentiation between languages at the univariate level (Hernandez et al., 2000, 2001; Rodriguez-Fornells et al., 2005). L2 speakers in the present study showed representational differences between L1 and L2 in areas that did not show activation differences, which suggests that while both languages engage the same areas to the same degree, each language has some level of unique population code within-area.

One possible limitation of the present study is the observed difference in imageability between Mandarin and English stimulus items. Mandarin words were rated more imageable than English words. Since ratings for either language were obtained from different cohorts of native speakers, and use a relatively objective scale, we are inclined to interpret this difference as reflecting a bias toward higher ratings in the Mandarin speakers rather than a veridical confound in our items. That said the difference does raise the possibility that observed fMRI differences in L1 vs. L2 representation are in fact a reflection of this imageability difference. However, we feel this is unlikely for several reasons. First, regions that showed more reliable representations in Mandarin than English were restricted to the left STG and the left IFG, which are more commonly associated with the acoustic and articulatory phonetic components of speech, respectively. While we did find separate language representations in right precuneus, a more classically visual area, the strength of the correlation did not differ between languages, indicating that languages were equally, but separately, represented in such

regions. Second, words in both languages were matched on how well they corresponded to their pictures, reducing the possibility that differences in representation could be due to differences between the levels of picture-word match between languages. Additionally, participants saw the same images in each set of language trials. Third, the simultaneous presentation of the word and picture minimizes the need for imagery. Thus, it is unlikely that differences in imageability are responsible for differences in representation of languages, although it cannot be entirely ruled out.

3.4.1   Conclusion

We investigated first and second language representation within the classical language network of English-Mandarin bilinguals. Using RSA, we identified regions both in which English and Mandarin were differentiated as well as regions in which they were not differentiated. Within-language representational similarity was present in classic language areas (i.e., portions of the left STG, MTG, and IFG), as well as the precuneus. The separate representation of L1 and L2 in these regions provides a possible mechanism for how bilinguals are able to process one language without interference from the other, while maintaining an integrated lexicon.

A logical extension of present study is the examination of representational differences in different types of second language processing. For instance, results may differ when comparing two languages that are more similar than English and Mandarin, such as Spanish and French, or when using items that vary in similarity, such as cognates and non-cognates. Univariate approaches that contrast degree of brain activation may miss important differences in this regard. The multivariate approach used here may thus provide a way forward in our ability to fully discern how L1 and L2 are represented in the brain.

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4 Age of second-language acquisition predicts white matter microstructure in bilinguals

4.1 Introduction

Acquiring a second language (L2) affects both the function and structure of the brain. These differences can be observed both when comparing monolinguals to bilinguals, and as a factor of individual differences within bilinguals. Between groups, there is greater neural activity in language regions in L2 compared to L1 during grammatical and lexical processing (Wartenburger et al., 2003; Sakai et al., 2004), greater gray matter density in the inferior parietal cortex in bilinguals versus monolinguals (Mechelli et al., 2004), and often greater white matter integrity and connectivity in bilinguals (Luk et al., 2011; Mohades et al., 2012a, 2015; Schlegel et al., 2012; García-Pentón et al., 2014). Within bilinguals, L2 shows greater levels of and more widespread brain activation than L1 (Rüschemeyer et al., 2005; Golestani et al., 2006; Jeong et al., 2007), as well as changes in white matter integrity as a function of individual differences (Nichols and Joanisse, 2016).

Bilinguals are a very heterogeneous group with respect to language experience; age of L2 acquisition (AoA), language learning experience (e.g., level of immersion in the second language; learning context such as group classes versus individual tutoring), current L2 proficiency, and time spent using each language over the course of the day all vary greatly between individuals. These individual differences also appear to affect both the structure and function of the brain (Pakulak and Neville, 2010, 2011; Newman et al., 2012a; Cummine and Boliek, 2013; Nichols and Joanisse, 2016), creating a challenge in describing the effects of bilingualism on the brain.

There are a number of methods used to study white matter microstructure in the brain, but a common technique is to measure fractional anisotropy (FA), which represents the directionality of water diffusion along white matter tracts (Basser, 1995; Basser and Pierpaoli, 1996; Pierpaoli and Basser, 1996). The FA of a particular tract depends on the number of axons in the tract, axon density, and myelination (Basser and Pierpaoli, 1996; Feldman et al., 2010). Other measures include mean diffusivity (MD), radial diffusivity

(RD), and tract volume (Feldman et al., 2010). Here, we focus on FA, which is the most common method used in studying white matter integrity in the bilingual brain and thus provides the most consistent form of comparison to past research.

While several tracts are known to underlie language processing, how these tracts are affected by L2 experience is still unclear. The arcuate fasciculus (AF) and superior longitudinal fasciculus (SLF) make up the dorsal connections between temporal and inferior frontal language areas, and have been widely implicated in language processing (Catani et al., 2005; Rilling et al., 2008). These two pathways are thought to be crucial to language function (Geschwind, 1970), supporting articulatory and phonemic functions (Leclercq et al., 2010) as well as grammatical and semantic processing in sentence comprehension (Brauer et al., 2011). Conflicting evidence has been found regarding the role of the AF/SLF in bilinguals, with some finding no differences in FA between monolinguals and bilinguals in the left AF/SLF (Mohades et al., 2012a, 2015) and others finding that FA in the bilateral AF/SLF is higher in bilinguals (Luk et al., 2011) or is modulated by AoA (Nichols and Joanisse, 2016). The inferior fronto-occipital fasciculus (IFOF) and the inferior longitudinal fasciculus (ILF) make up ventral pathways, the IFOF connecting frontal and posterior temporal regions (Catani et al., 2002; Jellison et al., 2004) and the ILF connecting occipitotemporal regions and the temporal pole (Catani et al., 2002; Vigneau et al., 2006; Mandonnet et al., 2007). The IFOF is known to support semantic processing (Duffau et al., 2005; Mandonnet et al., 2007; Leclercq et al., 2010) as it underlies temporal regions that map sound to meaning (Hickok and Poeppel, 2007), while the ILF is thought to indirectly support semantic function (Mandonnet et al., 2007). In bilinguals, both the bilateral ILF and IFOF have been shown to have higher FA in bilinguals relative to monolinguals (Luk et al., 2011; Mohades et al., 2012a, 2015). The bilateral ILF has also been shown to be modulated by individual differences (Nichols and Joanisse, 2016); however, the direction of the relationship conflicts with the hypothesis that bilinguals have higher FA, as FA was found to increase with increasing AoA.

Finally, the corpus callosum (CC) transmits information across hemispheres, and several studies of bilinguals have found differences between bilinguals and monolinguals in this tract (Coggins et al., 2004; Luk et al., 2011; Mohades et al., 2012; Schlegel et al.,

2012). Coggins and colleagues (2004) found greater area ratio of the anterior midbody to the rest of the CC in bilinguals relative to monolinguals, while Mohades and colleagues (2012) found lower FA in the anterior portion of the CC projecting to the orbital lobe in bilinguals compared to monolinguals.

The present study focuses on variability in AoA, a well-studied source of L2 variability in bilinguals. AoA predicts speech perception (Archila-Suerte et al., 2011), grammatical processing (Johnson and Newport, 1991; Weber-Fox and Neville, 1996; Wartenburger et al., 2003; Pakulak and Neville, 2011), and lexical processing (Isel et al., 2010; Nichols and Joanisse, 2016). AoA also influences the structure of the brain, likely due to maturational changes in plasticity as a person ages (Isel et al., 2010). Several studies have found increased tract volume and FA in bilinguals compared to monolinguals (Luk et al., 2011; Mohades et al., 2012a, 2015). Simultaneous bilinguals have also shown higher FA than sequential bilinguals (Mohades et al., 2012a, 2015). However, Mohades and colleagues (2012) found higher FA in the anterior portion of the CC extending to the orbitofrontal cortex in monolinguals than bilinguals. Similarly, Cummine and Boliek (2013) found higher FA in monolinguals in the right IFOF. Others have shown that FA increases with later AoA (Nichols and Joanisse, 2016), a finding that seemingly conflicts with the hypothesis that bilinguals have higher FA as a whole. Thus, the precise effect of AoA on white matter integrity remains unresolved.

It is likely that these conflicting results are due at least in part to methodological differences. First, white matter can be measured in numerous ways, and while the different measures (i.e., FA, MD, RD, and tract volume) are all conceptually related to one another, this is not a one-to-one mapping. Additionally, these measures are often averages of the entire tract of interest, which do not accurately reflect the microstructure in different sections of the tract. Second, bilingualism can be defined in many ways. There are simultaneous and sequential bilinguals, early and late learners, differing proficiency levels, and unbalanced and balanced bilinguals. Finally, there are a number of unrelated confounding variables that between group comparisons are inherently subject to, such as differing socioeconomic statuses, travel experience, and country of origin.

Here, we aimed to better understand the relationship between white matter microstructure and bilingualism. We describe differences in FA both between monolinguals and bilinguals, as well as within bilinguals as a function of individual differences. AoA was used as a measure of language experience, due to its known effects on both structure and function in bilinguals. Analyses were focused on four bilateral white matter tracts: the AF, ILF, IFOF, and SLF, as well as the CC. We predicted that these tracts would show between-group differences that would vary across the length of the tract, and that we would be able to show whether differences existed in either direction, given that prior literature has been inconsistent. We also predicted that ~~when~~ looking at AoA as a predictor of FA would lead to a more nuanced picture of how white matter microstructure is affected by L2 experience. Taking both between-group differences along the entirety of the tract into account with individual differences amongst bilinguals, we aimed to better describe the white matter of the bilingual brain, and account for the conflicting results in the present literature.

To do this, we used automatic fiber quantification (AFQ; Yeatman et al., 2012), a statistical toolbox that combines several advantageous features of various other software packages. First, tracts can be isolated based on probability maps (Hua et al., 2008), such that one can decide a priori which individual tracts to examine. Next, the tract can be divided into individual but continuous nodes so that FA is computed at each point along the tract. Because FA is not stable along the entire length of a white matter tract, this allowed a fine-grained analysis of how white matter microstructure differs at multiple points along each tract of interest. This is especially in relation to factors such as AoA, which has previously been shown to modulate FA in specific segments of white matter tracts (Nichols and Joanisse, 2016).

4.2 Method

4.2.1 Subjects

All participants ($n = 42$) spoke English as a first language. Group demographics are listed in Table 4.1. The 22 (13 female) monolingual (L1) participants, aged 18-54 ($M = 23.86$, $SD = 7.43$), were raised in an English-speaking household with little to no experience with other languages. They were tested at the University of Western Ontario, and scored between 64.58-100% on a test of English proficiency ($M = 89.78$, $SD = 7.51$; see below for details). The participant who scored lowest on the proficiency test performed most poorly on the vocabulary section. Excluding this participant, the lowest score in the English monolinguals was 81.8%.

The 20 (7 female) L2 speakers were native English speakers who were late L2 Mandarin learners, aged 20-37 ($M = 24.55$, $SD = 5.22$), and learned Mandarin between the ages of 13-28 ($M = 19.35$, $SD = 4.66$). L2 speakers scored between 22.92-72.92% ($M = 43.02$, $SD = 13.97$) on a test of Mandarin proficiency, and between 83.33-100% ($M = 91.35$, $SD = 3.96$) on a test of English proficiency. L2 speakers lived in Beijing for a variety of reasons; most were students on exchange programs or studying at Beijing Normal University, while others were working full time in China (e.g., teacher, accountant). Individuals were tested at Beijing Normal University. The research protocol was approved by the institutional review board (IRB) at Beijing Normal University and the University of Western Ontario. Prior to study participation, all participants gave informed consent. Groups did not differ significantly in age, years of education, socio-economic status, or English proficiency.

Table 4.1. Group demographics

Measure		Mean (SD)		t	p
		Monolingual	Bilingual		
Age (years)		23.86 (7.43)	24.55 (5.22)	-.34	.733
Sex	m	9	13		
	f	13	7		
Years of schooling		16.14	15.95	.24	.813
English proficiency		89.78 (7.51)	91.35 (3.96)	-.83	.410

4.2.2   Behavioural Materials

Prior to scanning, participants completed a subset of 48 questions from the Test of English as a Foreign Language (ETS, Princeton, NJ) to test English proficiency, and L2 speakers also completed a subset of 48 questions from the Hanyu Shuiping Kaoshi (HSK Centre, Beijing, China) to test Mandarin proficiency. Both tests consisted of three sections: Grammar, reading comprehension, and vocabulary. AoA was determined by asking L2 speakers to report the age at which they first began learning Mandarin. To verify handedness, participants completed an abridged version of the Edinburgh Handedness Inventory (Oldfield, 1971). All behavioural measures were completed in English aside from the Mandarin proficiency test. Letters of information, informed consent and task instructions were likewise administered in English.

4.2.3   DTI Acquisition and Preprocessing

Imaging was conducted on two Siemens Magnetom TIM Trio whole-body 3 Tesla scanners both equipped with a 32-channel head coil, located at the University of Western Ontario and at Beijing Normal University. All hardware and acquisition parameters were identical between scanners. A whole-head high-resolution 3D anatomical scan was acquired within the sagittal plane, using a 3D pulse sequence weighted for T1 contrast (MPRAGE; TR = 2.3 s; TE = 2.98 ms; FOV = 256 x 256 mm; voxel size = 1 mm^3; 176 slices; GRAPPA acceleration factor = 2). Diffusion-weighted images were acquired following the anatomical scan. Images were acquired in the axial plane using an EPI

imaging sequence (68 slices with 2 mm slice thickness, voxel size = 2.083 x 2.083 mm in-plane, matrix = 96 x 96 x 68, field of view = 200 mm^2, 64 diffusion directions with b = 1000 s/mm^2, TR = 7.6 s, TE = 79 ms; GRAPPA acceleration factor = 3).

DTI scans were processed and analyzed using the AFQ version 1.2 (Yeatman et al., 2012) and SPM8 toolboxes in MATLAB. Preprocessing consisted of motion and eddy current correction on the raw DTI data and alignment to the AC-PC aligned anatomical scan. Whole brain tractography was then initiated from each white matter voxel with an FA of >0.3 (Yeatman et al., 2012). Tracts were identified and segmented using waypoint ROI masks in standard space and transforming them to single-subject space (Wakana et al., 2007). The tracts of interest were then refined by comparing each fiber of each tract to probability maps defined by Hua et al., (2008). These tracts were the bilateral arcuate fasciculus, bilateral superior longitudinal fasciculus, bilateral inferior fronto-occipital fasciculus, and bilateral inferior longitudinal fasciculus, and the eight segments of the CC: the orbital frontal, anterior frontal, superior frontal, motor, temporal, superior parietal, posterior parietal, and occipital segments. Each tract was then cleaned into a compact bundle using an iterative procedure that removed fibers more than 4 standard deviations above the mean fiber length, or that deviated more than 4 standard deviations from the core of the fiber tract (Yeatman et al., 2012). To obtain spatially precise measures of FA, each tract was then divided into 100 equally spaced nodes along the length of the tract, and FA was calculated at each node. Participants whose FA contained values that were more than 4 standard deviations from the mean were excluded from analyses. This resulted in two bilingual participants and one monolingual participant being excluded, leaving 19 bilinguals and 21 monolinguals in the final analyses.

4.2.4   Analyses

To compare FA between groups, between-group *t*-tests were first calculated on mean FA of each tract. Next, *t*-tests were calculated at each node along the tract. In order to determine whether AoA explained group FA differences, the L2 group's tracts were then submitted to linear mixed effects modeling treating AoA as a continuous variable and subjects as a random variable, controlling for L2 proficiency. This also allowed us to

eliminate any between-group confounds that are inherent when comparing monolinguals to bilinguals. Correction for multiple comparisons at $p = .05$ was performed for each tract using a 1,000-iteration permutation test.

4.3 Results

4.3.1 Group Comparison

Results of the between-group two-tailed t-tests on mean FA revealed that mean FA was higher in monolinguals than in bilinguals in the left AF, SLF, IFOF, and ILF, as well as in the right IFOF. In the CC, mean FA was higher in monolinguals than in bilinguals in the anterior frontal, superior frontal, motor, temporal, and occipital segments ($t(38) > 4.18$, $p_{corr} < .05$ for all contrasts). Results of the t-tests after segmenting the tracts into 100 contiguous nodes are shown in Figure 4.1A and Figure 4.2. As shown in Figure 4.2, contrasts revealed that FA was greater in monolinguals than bilinguals in the dorsal section of the left AF and middle section of the left SLF. FA was also greater in monolinguals than bilinguals in the posterior section of the left ILF and large portions of both the left and right IFOF ($t(38) > 4.18$, $p_{corr} < .05$ for all contrasts). The right AF, right SLF, and right ILF did not show any between-group differences ($t(38) < 4.18$, $p_{corr} > .05$ for all contrasts). Contrasts were bonferroni corrected for multiple comparisons.

Results of the between-group comparisons of the segments of the CC are shown in Figure 4.1B and Figure 4.3. Left sections of the anterior frontal segment, middle and right sections of the superior frontal segment, middle and left sections of the motor segment and the temporal segment, and the middle sections of the superior parietal segment and the occipital segment all showed greater FA in monolinguals than bilinguals ($t(38) > 4.18$, $p_{corr} < .05$ for all contrasts). No group differences were found in the orbital frontal segment and posterior parietal segment, and no areas showed greater FA in bilinguals than monolinguals ($t(38) < 4.18$, $p_{corr} > .05$ for all contrasts).

4.3.2   Linear Mixed Effects of L2 Speakers

To examine how white matter integrity is related to L2 AoA, we performed LME on the bilingual data while controlling for L2 proficiency. This allowed us to identify regions of white matter in which FA uniquely predicted by AoA, and results of the intrahemispheric tracts are shown in Figure 4.4. AoA positively predicted FA in sections of the left dorsal AF ($r(18) > .62$, $p < .05$), left IFOF ($r(18) > .65$, $p < .05$), and left posterior ILF ($r(18) > .74$, $p < .05$), such that as AoA increased, so did FA. AoA also negatively predicted FA in sections of the left ($r(18) > -.65$, $p < .05$) and right IFOF ($r(18) > -.68$, $p < .05$), such that as AoA increased, FA decreased.

Results of the LME analysis on the CC are shown in Figure 4.5. The CC showed a pattern of results similar to the bilateral IFOF, with ~~both~~ sections positively correlated with AoA and other sections negatively correlating. The left hemisphere sections of the CC had more areas that correlated with AoA. Left orbital frontal ($r(18) > .72$, $p < .05$), superior frontal ($r(18) > .66$, $p < .05$), motor($r(18) > .65$, $p < .05$), superior parietal ($r(18) > .65$, $p < .05$), and occipital ($r(18) > .66$, $p < .05$) segments showed negative correlations with AoA, while left anterior frontal ($r(18) > .63$, $p < .05$), superior frontal, motor, temporal ($r(18) > .63$, $p < .05$), and posterior parietal ($r(18) > .67$, $p < .05$) segments showed positive correlations with AoA. There were fewer correlations in the projections to the right hemisphere, where the superior parietal and posterior parietal segments showed negative correlations with AoA, and the posterior parietal and temporal segments showed positive correlations with AoA. All p-values were Bonferroni corrected for multiple comparisons.
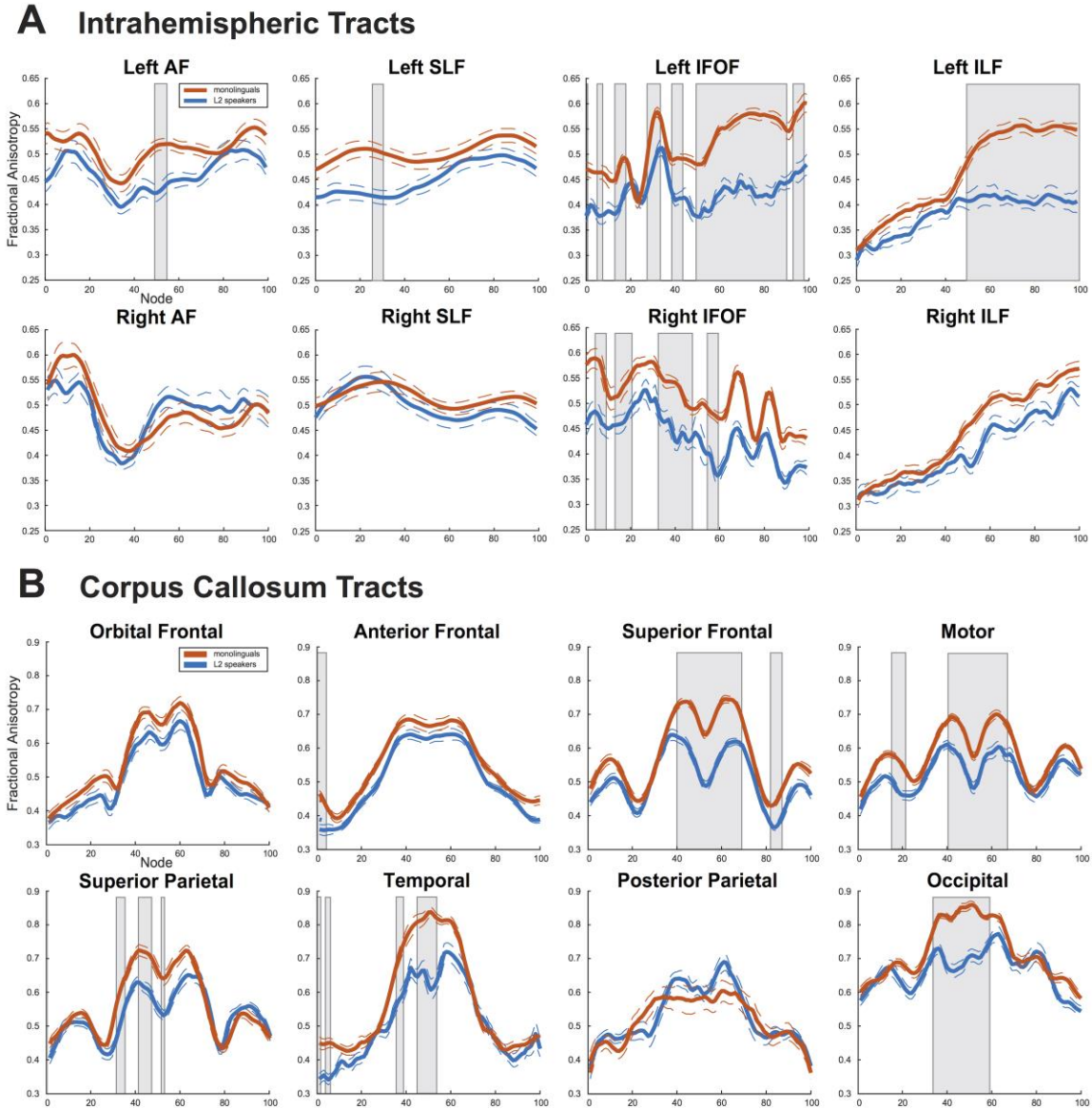
Figure 4.1. Tracts of interest were divided into 100 nodes (shown on the x-axis), and between-groups t-tests were computed at each node. Shaded sections indicate statistically significant differences between groups. A) Sections of the left arcuate fasciculus (AF), left superior longitudinal fasciculus (SLF), left inferior longitudinal fasciculus (ILF), and bilateral inferior fronto-occipital fasciculus (IFOF) showed greater FA in monolinguals than bilinguals. B) Similarly, sections of the CC showed greater FA in monolinguals than bilinguals. Dashed lines depict standard error. The x axis denotes each node extending from superior/anterior to inferior/posterior for intra-hemispheric tracts, and left to right for corpus callosum tracts.
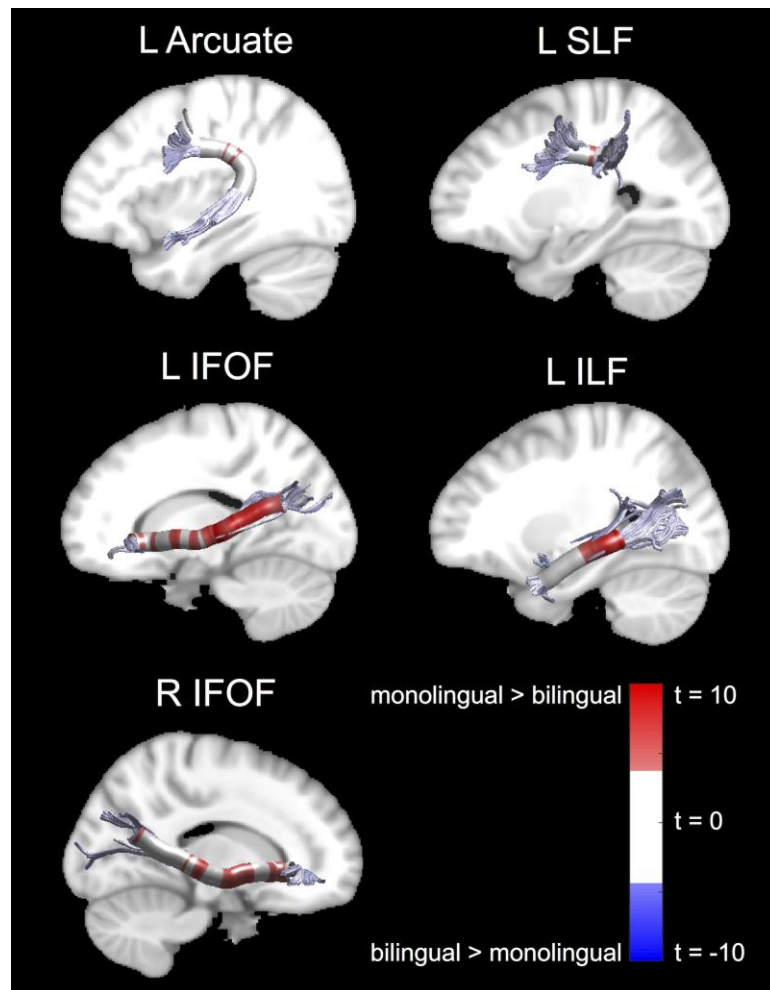
Figure 4.2. Sections of the left AF, left SLF, bilateral IFOF, and left ILF showed higher fractional anisotropy in monolinguals than in L2 speakers. Red sections of each tract show $t(38) > 4.18$, $p_{corr} < .05$.
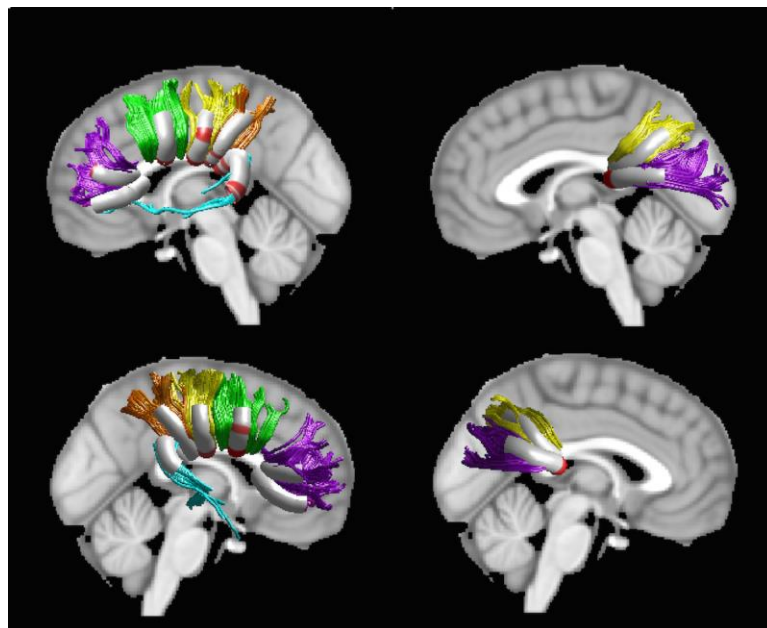
Figure 4.3. Segments of the CC showed higher fractional anisotropy in monolinguals than in L2 speakers. CC segments have been highlighted in different colors to differentiate them. Labels from anterior to posterior: orbital frontal, anterior frontal, superior frontal, motor, superior parietal, temporal, posterior parietal, occipital. Red sections of each tract show $t(38) > 4.18$, $p_{corr} < .05$.
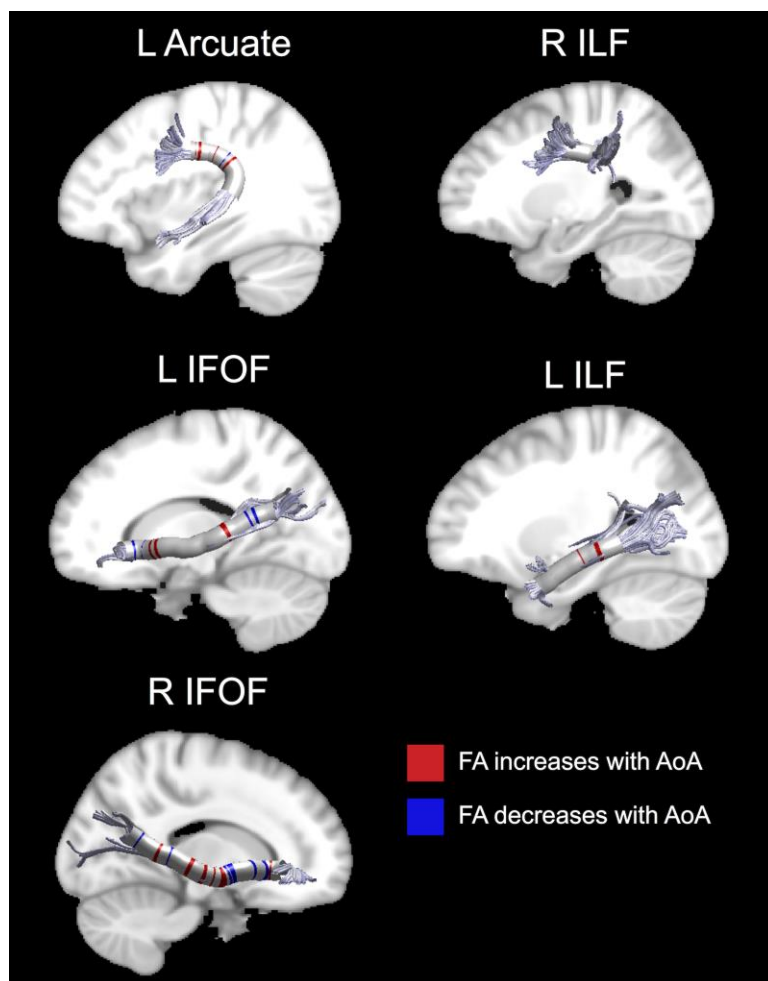
Figure 4.4. Fractional anisotropy in sections of the left AF and ILF showed a positive relationship with AoA in L2 speakers, shown in red. Sections of bilateral IFOF showed both positive (red) and negative (blue) correlations with AoA. $p_{corr} <$ .05 for all correlations.
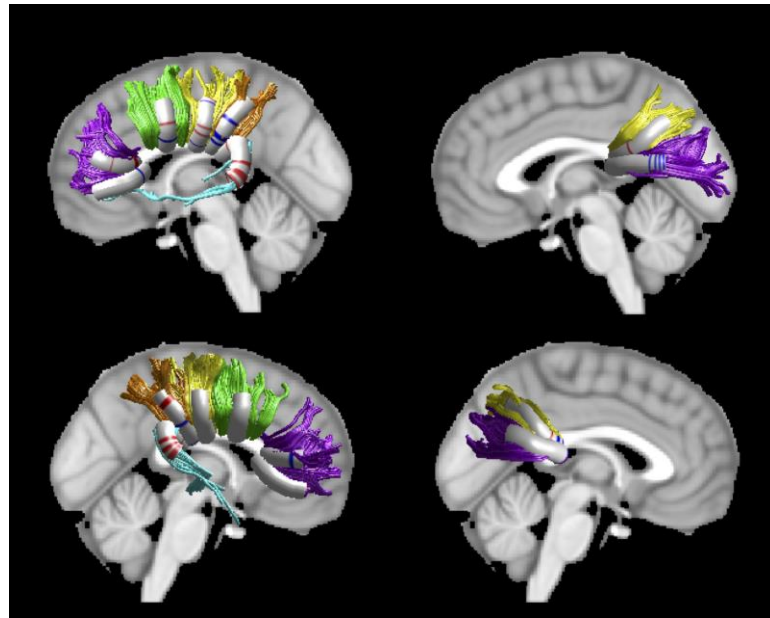
Figure 4.5. Sections of the CC showed both positive (red) and negative correlations with AoA, affecting left hemisphere projections more so than right hemisphere projections. $p_{corr} < .05$ **for all correlations.**

4.4 Discussion

The aim of this study was to examine the differences in white matter microstructure between monolinguals and L2 speakers. Previous DTI studies of bilinguals have returned conflicting results. A common way to examine white matter tracts is to isolate a tract and extract mean FA, which may not present an accurate description of the between-group differences. Additionally, there tends to be a large amount of heterogeneity amongst L2 speakers with respect to L2 language experience. Consistent with this, previous studies have found FA differences between simultaneous and sequential bilinguals (Mohades et al., 2012, 2015) and as a function of AoA (Nichols and Joanisse, 2016), suggesting that experience with L2 influences white matter differences between monolinguals and bilinguals. Thus, it is important to consider individual differences as a contributing factor to white matter microstructure in L2 speakers.

We examined the white matter tracts underlying language processing. In addition to group comparisons, which are inherently subject to group differences unrelated to bilingual status, we also examined white matter within the L2 group using AoA as a measure of the degree of language experience. We isolated four tracts bilaterally that have previously been implicated in bilingual language processing, the arcuate fasciculus, the superior longitudinal fasciculus, the inferior longitudinal fasciculus, and the inferior fronto-occipital fasciculus, as well as the eight segments of the CC. We then extracted measures of white matter coherence, namely FA, and compared across groups at 100 nodes along each tract. Because AoA has previously been shown to modulate specific segments of white matter tracts, calculating mean FA across an entire tract may not be sensitive to these modulations. Thus, dividing the tract into contiguous nodes provided a detailed description of white matter microstructure along the entire tract of interest, and how it relates to AoA.

Comparing across groups, we found evidence that monolinguals have higher FA than L2 speakers in sections of the left arcuate fasciculus, superior longitudinal fasciculus, inferior longitudinal fasciculus, and bilateral inferior fronto-occipital fasciculus, as well as in the anterior frontal, superior frontal, motor, superior parietal, occipital, and temporal segments of the CC (Figures 1 and 2). The left AF and SLF make up the dorsal stream underlying speech comprehension and articulation (Hickok and Poeppel, 2007), joining the temporal lobe with the inferior frontal gyrus and connecting key language processing areas (Saur et al., 2008; Duffau et al., 2002; Catani et al., 2005), and has been highly studied in its relationship to language processing (Geschwind, 1970; López-Barroso et al., 2013; Gullick and Booth, 2015). FA in the left AF is correlated with L1 reading ability (Yeatman et al., 2012; Gullick and Booth, 2015) and word learning (López-Barroso et al., 2013), and higher L2 AoA (Nichols and Joanisse, 2016). Distinction between the AF and SLF is difficult; the SLF may be part of the AF (Friederici, 2009) or a parallel tract (Duffau, 2008). The left SLF has also been implicated in reading ability (Yeatman et al., 2012). In in older adults, the SLF has been shown to have greater FA in bilinguals relative to monolinguals (Luk et al., 2011). Both the ILF and IFOF make up the ventral stream underlying semantic processing (Duffau et al., 2005; Mandonnet et al., 2007). In bilingual children, FA in the left IFOF has been

found to be higher in simultaneous bilinguals compared to both monolinguals and sequential bilinguals (Mohades et al., 2012a, 2015), however this difference was based on whole-tract measures of mean FA. The finding that the AF/SLF showed sensitivity to between- and within-group differences in the left hemisphere while the IFOF showed sensitivity bilaterally lends support to the dual-stream model of language processing (Hickok and Poeppel, 2007).

The CC transmits information between hemispheres, and the study of its relationship with bilingualism has produced conflicting results. Luk and colleages (2011) found higher FA in older bilinguals than older monolinguals in the CC, and Shlegel and colleagues (2012) found that FA in the genu of the CC increased as English speakers learned Mandarin. However, Mohades and colleagues (2012) found lower FA in bilinguals than monolinguals in the anterior CC extending to the orbital frontal lobe, while Gold and colleagues (2013) found lower FA in the splenium of the CC in bilinguals than monolinguals. The present results indicate that bilinguals have lower FA in several segments of the CC, including those with projections to the left hemisphere language areas such as the anterior frontal, superior frontal, and temporal segments. Additionally, individuals whose language function is strongly left-lateralized have higher FA in motor and sensory (i.e., superior parietal) segments of the CC (Westerhausen et al., 2006). Mandarin recruits more right-hemisphere brain areas than English, and may lead to less coherence within left hemisphere tracts. The present results support this hypothesis; monolinguals show greater FA in left hemisphere tracts including CC segments involved in language.

There are concerns that differences in FA are driven by spurious group differences unrelated to bilingual status, such as country of origin or international travel. One additional concern is that despite using identical scanners, the fact that groups were tested in different locations on separate scanners may confound between-group results. Thus, we also examined FA within the L2 group as a function of AoA. Within the left AF and ILF, FA increased with AoA (Figure 4.3), indicating that white matter microstructure increasingly resembles that of monolinguals in these tracts as age of second language acquisition increases. Similarly, FA increased with AoA within bilateral IFOF and

several segments of the CC. The increase in FA with increasing AoA supports the finding that monolinguals have higher FA in tracts underlying language processing. That is, English speakers who acquired Mandarin earlier had lower FA, and with increasing AoA, thus increasing time spent as a monolingual, FA also increased. However, in bilateral IFOF and the CC there were also sections in which FA negatively related to AoA, indicating that in these tracts the relationship is more variable. The directionality of the correlation between AoA and FA indicates that language experience shapes white matter pathways both positively, perhaps due to more enriched experience or compensatory mechanisms, and negatively, perhaps due to less time spent in one language vs. the other. That the within-group analysis led to results concordant with the between-group analysis indicates that the between-group differences were not due to differing scan locations.

The prior literature makes it difficult to understand the relationship between AoA and bilingualism, as well as the relationship between FA and bilingualism. Higher FA is often associated with more efficient language processing (Yeatman et al., 2012; López-Barroso et al., 2013; Gullick and Booth, 2015); for example, individuals who performed best in learning an artificial language had higher FA in left hemisphere tracts (López-Barroso et al., 2013). Consistent with this, several studies have observed increased FA in bilinguals relative to monolinguals, attributed to increased processing demands of maintaining two languages. Mohades and colleagues found higher FA in simultaneous bilinguals than both monolinguals (2012; 2015) and sequential bilinguals (2012) in left IFOF, with the authors suggesting that this may lead to faster semantic processing in bilinguals than monolinguals. Luk and colleagues (2011) found higher FA in older bilinguals than older monolinguals in the CC extending to bilateral SLF and right IFOF, and increased functional connectivity between frontal and posterior regions. The authors suggested that enriched experience protected white matter integrity from age-related deterioration.

However, the present finding of lower FA in bilinguals in language-related tracts is not unusual (Mohades et al., 2012; Cummine and Boliek, 2013; Nichols and Joanisse, 2016). Specifically, the positive correlation between FA and AoA replicates previous work in an unrelated but complementary sample of Mandarin-English L2 speakers

(Nichols and Joanisse, 2016). There, we used tract-based spatial statistics to identify areas of white matter in which AoA was positively associated with FA in the left CC and AF, and bilateral ILF. Similarly, other studies have shown that monolinguals have higher FA than bilinguals in the anterior portion of the CC projecting to the orbital lobe (Mohades et al., 2012a).

These results suggest that within tracts underlying language processing, experience with an L2, specifically Mandarin, has additional effects on white matter microstructure, although not in the often-predicted direction. This could be for a number of reasons. First, it is possible that speaking two languages reduces the coherence of these tracts; that is, dividing time between English and Mandarin also divides signal transmission, leading to lower FA. This would then have a greater impact the longer a bilingual speaks two languages, e.g., in those with earlier AoAs. In support of this hypothesis, it has been suggested that increased within-region activity may lead to lower between-region connectivity (Bennett & Rypma, 2013). Indeed, many studies have found greater activity in L2 compared to L1 (Dehaene et al., 1997; Kim et al., 1997; Perani et al., 1998; Wartenburger et al., 2003; Chee et al., 2004; Nichols and Joanisse, 2016). Second, a common issue in bilingualism research is with between-group comparisons (i.e., monolinguals vs. bilinguals); comparing between groups introduces a number of potential confounding variables that are not relevant to the bilingual status of the participants. For example, there are a number of life factors that may lead some individuals to become bilingual that may also affect white matter plasticity, such as socioeconomic status (Johnson et al., 2013; Ursache and Noble, 2016). Within-group analyses avoid these confounds, and in the present sample the positive relationship between FA and AoA supports the between-group comparison of higher FA in monolinguals. Finally, a group of bilinguals is generally fairly heterogeneous with respect to language experience, and individual differences in those experiences may be quite important. As the present results show, while group statistics suggest that L2 speakers as a whole may have lower FA, the within-group analysis reveals that this is a function of individual experience (i.e., AoA). Notably, one section of the left AF and several sections of bilateral IFOF showed increases in FA with decreasing AoA,

suggesting that the relationship between experience and white matter microstructure is more nuanced than can be accounted for by whole-tract analyses.

The present study examined English-Mandarin bilinguals, which may limit the interpretation of the results to these languages. Mandarin has shown greater right hemisphere activation than other languages (Ren et al., 2009; Li et al., 2010), which likely also modulates white matter in the right hemisphere. Indeed, greater FA in the right SLF and ILF is predictive of both Mandarin spoken and written learning success (Qi et al., 2015). Although the involvement of the right IFOF supports the dual-stream hypothesis, it is possible that here, the IFOF is supporting Mandarin processing rather than language processing in general. Future research is needed to determine whether the present results extend to other languages.

Thus, it remains unclear what the relationship between FA and degree of bilingual experience actually reflects. While bilingual experience may shape our white matter pathways, it is also possible that individuals with greater white matter integrity may be more likely to begin second language learning later in life. Looking toward future studies, a major challenge will be to explore the causal relationship between white matter, bilingualism, and individual differences in language experience using a longitudinal approach. Examining monolingual speakers before beginning to learn an L2, or monolinguals and bilinguals early and late in life would both allow for within-subject analyses, reducing the impact of the confounds that introduce themselves in observational studies.

4.4.1   Conclusion

Recently, the importance of white matter pathways in relation to bilingualism has become evident. In the present study we examined this relationship with regard to language-related white matter tracts in the brain, using a statistically robust approach. Of note, we adopted both a between- and within-subjects approach in order to better ascertain how differences between monolinguals and bilinguals relate specifically to individuals' second language experience. The results provide support for a left-lateralized dorsal stream and a bilateral ventral stream underlying language. The results also suggest

that language experience has a notable impact on white matter microstructure of the bilingual brain, an effect that is more nuanced than previously thought.

4.5   References

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5 Accounting for individual differences in theories of bilingual language processing

Despite large amounts of variance in L2 speakers, such as AoA and proficiency level, most theories of bilingualism treat bilingual language processing and acquisition as uniform processes that are applicable to all. Research has begun to account for individual differences along such parameters as AoA; however, accounts of the effects of these individual differences are generally limited to particular parts of language, such as grammar. In this dissertation, I addressed this issue by characterizing the effect of individual differences on several parts of bilingual language processing in the brain, with the aim of making specific recommendations as to how current neurocognitive theories could be modified to include individual differences. In this chapter, I will begin by summarizing the relevant findings in chapters 2, 3, and 4. Next I discuss where individual differences come from. Finally, I will end by making recommendations for current theories of bilingualism, with considerations for future work.

5.1 Relevant Findings

5.1.1 Individual differences interact with similarities across L1 and L2

For theories of bilingual language processing, it is essential to consider the interactions of individual differences with similarities and dissimilarities across L1 and L2. To examine this, I compared processing of a novel grammatical rule, grammatical gender, and a grammatical rule that is similar across languages, phrase structure, across native and L2 speakers of French. Grammatical gender is the grammatical construct in which nouns have a specific gender, and other parts of language are inflected or conjugated to account for this gender. Grammatical gender does not exist in English, while it is a prevalent grammatical rule in French that implicates various parts of language including nouns, articles, and adjectives. Phrase structure is a rule that dictates how words in a phrase can be ordered. For example, in both English and French, the article (*the*/*le*) must precede the noun (*table*), rather than follow it (*table the*/*le*). However in French the exact article used (le/la) must match the noun. L2 speakers must learn

grammatical gender as a novel rule, rather than one that is similar across languages, which leads to differing patterns of neural responses to each type of error (Salamoura and Williams, 2007; Frenck-Mestre et al., 2009; Foucart and Frenck-Mestre, 2011, 2012; Wicha et al., 2012; Rossi et al., 2014). Again, because English-French bilinguals vary greatly in their L2 language experience, I was interested in whether individual differences in AoA and proficiency could predict how native-like the novel rule would be processed, or whether L2 status alone, i.e., speaking French as an L2, would predict the neural response to the novel rule.

The ERP study reported in Chapter 2 offers evidence that both AoA and proficiency, in addition to L2 status, modulate processing of a novel L2 grammatical rule. In contrast, only proficiency predicted processing of a grammatical rule that is similar across languages. Native French speakers and L1 English-L2 French speakers read French sentences that were either correct or contained a grammatical gender or structure violation. Analyses revealed that early (300-500 ms) in the processing stream, AoA predicted the neural response to novel grammatical rules, whereas proficiency predicted LAN amplitude to grammatical rules that are similar across languages. Later in the processing stream (500-800 ms), AoA, proficiency, and group membership (L1 vs. L2) predicted the neural response to novel grammatical rules, whereas no response was elicited to similar rules. These findings add to the existing literature showing that there is effect of similarities between languages on second language processing (Sabourin et al., 2006; Salamoura and Williams, 2007; Lemhöfer et al., 2008; Foucart and Frenck-Mestre, 2011; Gillon Dowens et al., 2011). The results of Chapter 2 take this knowledge a step further by showing that while the similarities between languages affect L2 processing, the degree of their influence is modulated by individual differences in L2 experience, specifically AoA and proficiency. Thus, both novel and similar L2 grammatical processing is sensitive to individual differences, suggesting that models of L2 processing must account for these differences.

5.1.2 Languages are represented differently in certain shared cortical areas

A recurring theme in theories of bilingual language processing is that of a shared, integrated lexicon, however the neurobiological basis for this tenet is unclear. Studies of balanced bilinguals suggest that there are no differences between the areas of activation in L1 and L2 (Chee et al., 1999b; Hernandez et al., 2000, 2001; Rodriguez-Fornells et al., 2005; Indefrey, 2006), suggesting that both languages share the same neural resources. While these studies support a shared, integrated lexicon, it remains unclear how languages are then kept separate, allowing bilinguals to function in one language with no intrusion of the other. Because a shared lexicon is a generally agreed-upon aspect of bilingual language processing, Chapter 3 sought to describe how this is neurobiologically realized. I predicted that in response to single words in each language, shared regions between L1 and L2 would show different patterns of activation that were more similar within-language than between-language. I also predicted that representational dissimilarity between languages would occur in classic language regions, with domain-general regions showing no distinction between L1 and L2.

Using RSA, I provided evidence that within cortical regions involved in word recognition, classic language areas such as the left IFG, STG, and MTG showed patterns of activity that correlated more within-language than between, in addition to the right precuneus. That is, languages were being neurally represented differently in these areas. As a group, the sample of English-Mandarin bilinguals in Chapter 3 was of late AoA and had lower L2 proficiency than L1 proficiency. These differences between L1 and L2 were likely reflected in the contrast between L2 and L1; L2 showed greater activation than L1 in several brain regions. Of note however is that none of the areas that showed representational dissimilarity between languages showed differences in activation levels in the contrast, supporting the hypothesis of an integrated lexicon. Although it is impossible to interpret a lack of activation differences, it is possible that the representation of each language is not sensitive to L1/L2 differences in AoA or proficiency, which future research should explore. The separate representation of L1 and

L2 in these regions provides a possible mechanism for the neurobiological realization of a shared, integrated lexicon proposed by many theories of bilingualism.

5.1.3 Language experience impacts white matter microstructure of the bilingual brain

L2 language experience affects not only brain function, but also brain structure (Chen et al., 2007; Luk et al., 2011; Mohades et al., 2012b, 2015; Cummine and Boliek, 2013; García-Pentón et al., 2014; Li et al., 2014; Nichols and Joanisse, 2016). Although it is generally thought that bilinguals have better, more coherent white matter tracts, several studies have found contradicting evidence (Mohades et al., 2012b; Cummine and Boliek, 2013; Nichols and Joanisse, 2016). Comparing between groups, especially between groups of monolinguals and bilinguals, is unfortunately complicated by other group differences unrelated to those of interest. There are a number of life factors that may lead some individuals to become bilingual that may also affect white matter plasticity, such as socioeconomic status (Johnson et al., 2013; Ursache and Noble, 2016). Additionally, methods vary between studies, with most taking the mean FA of a tract of interest, which may not capture how white matter integrity changes along its length. Chapter 4 examined whether between group differences in white matter microstructure was modulated by one measure of L2 language experience, that of AoA. I predicted that there would be differences in white matter when comparing groups, and that accounting for AoA would provide a more nuanced description of how individual differences among bilinguals can account for white matter microstructure.

Using DTI, I examined white matter tracts in the left and right hemispheres that underlie language processing, and have shown differences between bilinguals and monolinguals; the bilateral AF, SLF, IFOF, and ILF, as well as the CC. In each of the left tracts, the right IFOF and segments of the CC, monolinguals had higher FA (a measure of white matter integrity) than bilinguals. Within bilinguals, FA in the left AF and ILF increased with increasing AoA, while FA in the IFOF and CC showed both positive and negative correlations with AoA. Thus, while group statistics suggest that L2 speakers as a whole may have lower FA, the within-group analysis revealed that white matter integrity is sensitive to individual experience (i.e., AoA). Theories of bilingualism have begun to

account for the observed patterns of activity in the brain. However, white matter structure may influence the patterns of activity observed, and structure is sensitive to individual differences.

5.2   Where do individual differences come from?

Bilinguals are a wholly variable group of individuals, and this is a result of a combination of both biology and environment. The environment itself is multifactorial – there are external factors such as teaching strategy, immersion in an L2 environment, or interaction with L2 speakers such as friends, neighbours, or caretakers, the manner of L2 acquisition, as well as the context in which each language is used and the amount of L2 exposure, separate from AoA (Whitford and Titone, 2012). There are also internal factors such as motivation. Additionally, the line between biology and environment is blurry; is the age at which second language learning begins biological or environmental? While the reasons for L2 learning may be environmental – such as moving to a new country – the effect that is has may be biological, due to the developmental stage the learner is in.

The issue of innateness is often discussed in relation to second languages. Theories of bilingualism tend to focus on whether the innateness of a first language, that is, the ease of which a first language is acquired and mastered, is available to a second language. However, this concept is premised on the assumption that native speakers do not vary in their L1 ability, which is incorrect; native speakers can vary in their level of proficiency, and show differences at the neural level in response to both syntactic and semantic violations (Weber-Fox et al., 2003; Pakulak and Neville, 2010; Newman et al., 2012b). Individual differences play a role beyond native or L2 status, which is often assumed to be the major contributing factor to differences between L1 and L2.

5.3   Recommendations and directions for future research

While some progress has been made towards a neurocognitive theory of bilingual language processing, the research reported in this dissertation generates additional questions and motivates future work. First, the direction of causality between brain, behaviour, and environment in relation to the different aspects of bilingualism must be

determined. This is a complex problem, because these three factors are highly interconnected. An example of such questions is: Do late L2 learners have different brain structure than native speakers because they learned the L2 after the brain had lost some plasticity? Or are the observed differences in brain structure between late L2 speakers and native speakers what allow the late learners to acquire an L2 so late in life? Are people who are "hard-wired" for easy L2 acquisition more likely to find themselves in an immersive L2 environment, or does immersion simply lead to better learning outcomes? Current imaging such as fMRI, DTI, and voxel-based morphometry combined with longitudinal designs are particularly promising for answering such questions, and have already begun to be employed (Li et al., 2014; Mohades et al., 2015; Qi et al., 2015). Longitudinal designs necessarily lay beyond the scope of a four-year doctorate. However, the research presented in this dissertation lays a foundation for how future research can be both designed and analyzed using a longitudinal approach. For example, by following children from the time they begin French immersion, to the time they graduate high school, factors such as initial white matter microstructure could reveal insights into who will be most successful in learning French. Such findings could in turn inform theories and models of second-language teaching and bilingualism by better explaining how the end-point of language learning is influenced by pre-existing biological factors.

Second, a complete neurocognitive model must describe how the cognitive constructs of bilingualism are realized in the brain. While several theories have described the processes that must occur for bilingual language processing to occur, such as relaying lexical information through L1 (Kroll and Stewart, 1994; Kroll et al., 2010), it remains unclear how this process occurs in the brain. The brain areas involved have also been examined, such as the left temporal regions involved in the lexical system of the declarative/procedural model (Ullman, 2001a, 2004). However, describing the brain regions involved falls short of describing then how lexical information is transferred from L2 to L1 (e.g., is this within a brain region? Are there longer-range connections involved in this process?), or how the grammatical knowledge gradually switches from declarative to procedural memory. Analyses of functional and structural connectivity will prove important for describing these neural processes, as they examine how different regions in the brain communicate and how they are structurally connected.   Finally, a complete

neurocognitive theory of bilingualism must continue to take individual differences into account, because no two bilinguals are alike. Several models of bilingual language processing recognize the importance of individual differences, and attempt to account for them within their framework. The Bilingual Interactive Activation Plus (BIA+; Dijkstra and van Heuven, 2002) model describes how low proficiency results in low resting activation of items at the sublexical, lexical, and semantic levels, which increase with increasing proficiency. Similarly, the Revised Hierarchical Model (RHM; Kroll and Stewart, 1994) describes how strength of word-concept mappings are modulated by proficiency. The declarative/procedural model (DP; Ullman, 2001a, 2001b) takes both AoA and proficiency into account, although it provides stronger predictions for the effects of individual differences on syntactic than semantic systems. However, although each of these models takes AoA and/or proficiency into account, there are many individual differences affecting bilingual language processing, such as context in which each language is used (e.g., school vs. home), balance of time spent speaking each language (e.g., more time spent in L2 than L1), and method of acquisition (e.g., a class in school vs. an immersion program), that remain to be accounted for. While this dissertation has examined two of those factors, AoA and proficiency, other sources of individual differences are currently under-examined, and future research will need to take them into account to better understand the environmental factors influencing L2 learning success.

As this dissertation has explored, there is a large amount of variability between bilinguals in both brain and behaviour. Thus, when considering the results of studying a particular set of bilinguals, the contributions of individual differences in AoA, proficiency level, and other factors should be considered. Indeed, chapters 2 and 4 of this dissertation showed how individual differences modulate novel/similar grammatical processing and white matter microstructure, and several other studies have described their effects on other linguistic aspects such as semantic processing (Wartenburger et al., 2003; Newman et al., 2012b; Nichols and Joanisse, 2016). While theories of bilingualism are beginning to address these concerns, such as describing how reliance on memory systems underlying grammatical processing changes with proficiency, there is yet to be a theory that can fully account for the range of individual differences represented in the bilingual

population. To fully understand bilingual language processing, we must integrate all three of these recommendations. With causality, neural realization of cognitive constructs, and individual differences, a comprehensive neurocognitive theory of bilingual language processing can be developed.

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Appendices

Appendix A - L2 demographic and behavioural variables

Subject	Sex	Age of first exposure to French (years)	Age at testing (years)	Years of formal French education	Total years French exposure	Proficiency score (% correct)
L2-01	F	9	23	13	14	73
L2-02	F	9	27	8	18	81
L2-03	F	6	22	13	16	57
L2-04	F	5	21	12	16	55
L2-05	F	5	23	13	18	77
L2-06	F	8	20	10	12	49
L2-07	F	5	19	13	14	66
L2-08	F	5	19	12	14	66
L2-09	F	8	21	12	13	91
L2-10	F	9	33	6	24	67
L2-11	F	8	18	9	10	72
L2-12	M	10	18	7	8	32
L2-13	M	4	18	10	14	37
L2-14	F	3	20	14	17	51
L2-15	F	0	19	15	19	80
L2-16	F	4	22	14	18	68
L2-17	F	15	18	9	3	53
L2-18	M	16	19	8	3	55
L2-19	M	10	26	16	16	63
L2-20	F	5	23	16	18	88

Appendix B – Language History Questionnaire

1. What languages/dialects have you been surrounded by from birth up to now?

- List only those languages you were exposed to for at least 3 months or so, for at least a few hours a day. Pay special attention up to age 18.

- **Indicate the dialect as well**, e.g., Standard Canadian English, Acadian French, Quebecois French, Canadian School French, Southern American English, Black English, Standard British English, etc.

- Give a broad estimate of how much time was devoted to listening and speaking in each language over the entire period. Use the following scale:

Rarely	Occasionally	Quite A bit	Almost all the time	All the Time
1	**2**	**3**	**4**	**5**

- If you spent more or less time using one language at different times in your life, list each time period separately. See the examples below.

Example 1: Marie grew up in Montréal in a French family. She took English classes a few hours a week in school, and went on an English exchange program when she was 15. Now she attends University in Halifax and uses French only with a few friends and when calling or visiting family.

Language/ Dialect	Geographical place(s)	Start Age	End Age (-1 if current)	Time in Language		Comments
				Listening	Speaking	
Quebec French	Montreal	0	6	5	5	
French	Montreal	6	18	4	4	
School English	Montreal	6	18	2	2	
Canadian English	Winnipeg	15	15	4	4	Exchange
English	Halifax	18	-1	4	4	
French	Halifax	18	-1	1	1	

Example 2: Peter was born in Halifax and started late French immersion when he was 13. Since graduating from high school he works for the government in a customer service position where he speaks both French and English.

Language/ Dialect	Geographical place(s)	Start Age	End Age (-1 if current)	Time in Language		Comments
				Listening	Speaking	
English	Halifax	0	13	5	5	
English	Halifax	13	-1	3	3	
Canadian school French	Halifax	13	-1	3	3	

Now fill in your own language history, using this scale:

Rarely	Occasionally	Quite A bit	Almost all the time	All the Time
1	2	3	4	5

Language/ Dialect	Geographical place(s)	Start Age	End Age (-1 if current)	Time in Language		Comments
				Listening	Speaking	

Comments:

2. List **all the languages/dialects that you currently know**

- Please indicate how well you currently speak, understand, read, and write each language using the following number scale:

Badly	Adequately	Quite Well	Almost Fluently	Like a Native Speaker
1	**2**	**3**	**4**	**5**

Language/ Dialect	Speak	Understand	Read	Write	Comments

3. If you were substantially more proficient at a language/dialect in the past than you are now (or if you no longer know a language at all that you knew in the past), please indicate how well you spoke, understood, read, and wrote each language or dialect *when you knew it best,* using the same 1-5 scale as question 2, above:

- Please also indicate what your age was just before your proficiency in the language began to decline (e.g., after emigration, after living abroad, after taking language classes).

Language/ Dialect	Age before decline	Speak	Understand	Read	Write	Comments

4. List all **formal language instruction**, paying special attention up to age 18 (especially if the number of hours of instruction changed at different ages/grade levels).

- Only include language instruction, not other subjects taught in a given language.

- Include instruction in **both your native and non-native languages**.

- If the period was less than one year, give the same start and end ages.

- *End Age:* Enter -1 if currently taking instruction
- *Type of Instruction*: **S** = School; **IM** = immersion (in school); **LI** = Language Institute; **PI** = Private Instructor; **O** = Other (specify in Comments).

- *Teachers*: only Native Speakers (**NS**) of the language being taught; only Non-Native Speakers (**NNS**), or (if multiple teachers), both NS and NNS (**BOTH**).

- *Hours/week* refers to the approximate number of hours of language instruction per week.

Language/ Dialect	Start Age	End Age	Type of Instruction	Teachers	Hours/ week	Comments

Comments:

Appendix C – Chapter 2 experimental items

	Correct control	Gender violation	Structure violation
1	J'ai acheté <u>la robe</u> en ville.	J'ai acheté <u>le robe</u> en ville.	J'ai acheté <u>robe la</u> en ville.
2	Après avoir reçu <u>ma confession</u> il va recevoir nos serments.	Après avoir reçu <u>mon confession</u> il va recevoir nos serments.	Après avoir reçu <u>confession ma</u> il va recevoir nos serments.
3	Le voisin qui peut découvrir <u>le trésor</u> a une pelle.	Le voisin qui peut découvrir <u>la trésor</u> a une pelle.	Le voisin qui peut découvrir <u>trésor le</u> a une pelle.
4	Vous devez nettoyer <u>le comptoir</u> avant de quitter.	Vous devez nettoyer <u>la comptoir</u> avant de quitter.	Vous devez nettoyer <u>comptoir le</u> avant de quitter.
5	Jacqueline sera sur scène pour <u>une représentation</u> ce soir.	Jacqueline sera sur scène pour <u>un représentation</u> ce soir.	Jacqueline sera sur scène pour <u>représentation une</u> ce soir.
6	Pour soutenir <u>sa famille</u> elle travaille dès un jeune âge.	Pour soutenir <u>son famille</u> elle travaille dès un jeune âge.	Pour soutenir sa famille elle <u>dès travaille</u> un jeune âge.
7	L'hallucination est <u>une folie</u> momentanée.	L'hallucination est <u>un folie</u> momentanée.	L'hallucination est <u>folie une</u> momentanée.
8	Le patient a été rassuré par <u>le renseignement</u> peu précis.	Le patient a été rassuré par <u>la renseignement</u> peu précis.	Le patient a été rassuré par <u>renseignement le</u> peu précis.
9	Cette sensation de soleil dans <u>la nature</u> est un vrai plaisir.	Cette sensation de soleil dans <u>le nature</u> est un vrai plaisir.	Cette sensation <u>soleil de</u> dans la nature est un vrai plaisir.
10	Une volée de colombes était piégée dans <u>un filet</u> de chasseurs.	Une volée de colombes était piégée dans <u>une filet</u> de chasseurs.	Une volée de colombes était piégée dans <u>filet un</u> de chasseurs.
11	J'ai eu du plaisir à jouer dans <u>la neige</u> cette semaine.	J'ai eu du plaisir à jouer dans <u>le neige</u> cette semaine.	J'ai eu du plaisir à <u>dans jouer</u> la neige cette semaine.
12	Le vapeur va retourner à la terre dans <u>la forme</u> de la pluie.	Le vapeur va retourner à la terre dans <u>le forme</u> de la pluie.	Le vapeur va retourner à la <u>dans terre</u> la forme de la pluie.
13	Il faut que je cherche un emploi	Il faut que je cherche un emploi	Il faut que je cherche un <u>pour</u>

	pour payer <u>ma voiture</u> d'occasion.	pour payer <u>mon voiture</u> d'occasion.	<u>emploi</u> payer ma voiture d'occasion.
14	Le soir Danielle aime voir <u>son ombre</u> s'allonger.	Le soir Danielle aime voir <u>sa ombre</u> s'allonger.	Le soir Danielle aime voir <u>ombre son</u> s'allonger.
15	On passait au salon pour <u>le café</u> après le dîner.	On passait au salon pour <u>la café</u> après le dîner.	On passait au salon pour <u>café le</u> après le dîner.
16	Elle a apporté <u>le document</u> à l'entreprise.	Elle a apporté <u>la document</u> à l'entreprise.	Elle a <u>le apporté</u> document à l'entreprise.
17	La France est <u>un pays</u> merveilleux.	La France est <u>une pays</u> merveilleux.	La France est <u>pays un</u> merveilleux.
18	Les trois frères arrivent à <u>un château</u> ensorcelé.	Les trois frères arrivent à <u>une château</u> ensorcelé.	Les trois <u>arrivent frères</u> à un château ensorcelé.
19	Elle adorent les couleurs d'automne et <u>le bruit</u> des feuilles sèches.	Elle adorent les couleurs d'automne et <u>la bruit</u> des feuilles sèches.	Elle adorent les <u>d'automne couleurs</u> et le bruit des feuilles sèches.
20	Le bruit qui réveille <u>le village</u> est très suspect.	Le bruit qui réveille <u>la village</u> est très suspect.	Le bruit qui <u>le réveille</u> village est très suspect.
21	La voisine remplit <u>le placard</u> après avoir fait les courses au marché.	La voisine remplit <u>la placard</u> après avoir fait les courses au marché.	La voisine remplit le placard <u>avoir après</u> fait les courses au marché.
22	Le pêcheur qui peut piloter <u>le bateau</u> a son permis.	Le pêcheur qui peut piloter <u>la bateau</u> a son permis.	Le pêcheur qui <u>piloter peut</u> le bateau a son permis.
23	L'homme posa <u>le sac</u> sur la table.	L'homme posa <u>la sac</u> sur la table.	L'homme posa le <u>sur sac</u> la table.
24	Depuis <u>le début</u> toutes les participantes travaillaient d'arrache-pied.	Depuis <u>la début</u> toutes les participantes travaillaient d'arrache-pied.	Depuis le début toutes participantes les travaillaient d'arrache-pied.
25	Je vais acheter <u>une chemise</u> avec mon père.	Je vais acheter <u>un chemise</u> avec mon père.	Je vais <u>une acheter</u> chemise avec mon père.

26	Le voyageur s'est amusé dans <u>le parc</u> aquatique.	Le voyageur s'est amusé dans <u>la parc</u> aquatique.	Le voyageur s'est amusé dans <u>parc le</u> aquatique.
27	Il portait <u>son costume</u> habituel.	Il portait <u>sa costume</u> habituel.	Il portait <u>costume son</u> habituel.
28	Il a dessiné <u>une image</u> sur le mur.	Il a dessiné <u>un image</u> sur le mur.	Il a dessiné <u>image une</u> sur le mur.
29	Elle portait des sandales car <u>le sable</u> est très chaud.	Elle portait des sandales car <u>la sable</u> est très chaud.	Elle portait <u>sandales des</u> car le sable est très chaud.
30	Le garçon qui aime <u>la poupée</u> est tout petit.	Le garçon qui aime <u>le poupée</u> est tout petit.	Le garçon qui aime <u>poupée la</u> est tout petit.
31	Sa copine ouvre <u>la porte</u> lentement.	Sa copine ouvre <u>le porte</u> lentement.	Sa copine <u>la ouvre</u> porte lentement.
32	L'air est frais et rempli par <u>le chant</u> des oiseaux.	L'air est frais et rempli par <u>la chant</u> des oiseaux.	L'air est frais et rempli par <u>chant le</u> des oiseaux.
33	Un jour ils ont aperçu <u>une pelle</u> au détour d'un sentier.	Un jour ils ont aperçu <u>un pelle</u> au détour d'un sentier.	Un jour ils ont aperçu <u>pelle une</u> au détour d'un sentier.
34	J'aimerais acheter <u>une pomme</u> mais ce n'est pas possible.	J'aimerais acheter <u>un pomme</u> mais ce n'est pas possible.	J'aimerais acheter une pomme <u>ce mais</u> n'est pas possible.
35	Il adore manger <u>le fromage</u> avec de trous comme le gruyère.	Il adore manger <u>la fromage</u> avec de trous comme le gruyère.	Il adore manger le <u>avec fromage</u> de trous comme le gruyère.
36	La lueur tremblotante d'<u>une chandelle</u> éclaire cette chambre.	La lueur tremblotante d'<u>un chandelle</u> éclaire cette chambre.	La lueur tremblotante d'une <u>éclaire chandelle</u> cette chambre.
37	Nous allons recevoir <u>une visite</u> d'un client importante.	Nous allons recevoir <u>un visite</u> d'un client importante.	Nous allons <u>une recevoir</u> visite d'un client importante.
38	Le voleur qui peut briser <u>la statue</u> est assez rapide.	Le voleur qui peut briser <u>le statue</u> est assez rapide.	Le voleur qui peut <u>la briser</u> statue est assez rapide.
39	Il a fait ses devoirs <u>la semaine</u> dernière.	Il a fait ses devoirs <u>le semaine</u> dernière.	Il a fait <u>devoirs ses</u> la semaine dernière.

40	Vous allez devoir subir <u>une opération</u> chirurgicale.	Vous allez devoir subir <u>un opération</u> chirurgicale.	Vous allez devoir subir <u>opération une</u> chirurgicale.
41	Le mécanicien qui peut réparer <u>la machine</u> est en retard.	Le mécanicien qui peut réparer <u>le machine</u> est en retard.	Le mécanicien qui réparer <u>peut la</u> machine est en retard.
42	Le marchand qui a fermé <u>le magasin</u> a trois clés.	Le marchand qui a fermé <u>la magasin</u> a trois clés.	Le marchand qui a fermé <u>magasin le</u> a trois clés.
43	Il ya une prison dans <u>la ville</u> d'à côté.	Il ya un prison dans <u>la ville</u> d'à côté.	Il ya une <u>dans prison</u> la ville d'à côté.
44	Une naissance extraordinaire bouleversa <u>la planète</u> Terre.	Une naissance extraordinaire bouleversa <u>le planète</u> Terre.	Une naissance <u>bouleversa extraordinaire</u> la planète Terre.
45	J'ai nagé dans <u>la piscine</u> tous les jours.	J'ai nagé dans <u>le piscine</u> tous les jours.	J'ai nagé dans <u>piscine la</u> tous les jours.
46	Pendant <u>le film</u> ma mère faisait du pop-corn.	Pendant <u>la film</u> ma mère faisait du pop-corn.	Pendant le film <u>mère ma</u> faisait du pop-corn.
47	Il vivait en Allemagne depuis trois ans lorsque <u>la guerre</u> a commencé.	Il vivait en Allemagne depuis trois ans lorsque <u>le guerre</u> a commencé.	Il vivait en Allemagne depuis <u>ans trois</u> lorsque la guerre a commencé.
48	Vous allez voir <u>la banque</u> à votre gauche.	Vous allez voir <u>le banque</u> à votre gauche.	Vous allez voir <u>banque la</u> à votre gauche.
49	Le moine a été perturbée par <u>un fracas</u> dehors.	Le moine a été perturbée par <u>une fracas</u> dehors.	Le moine a <u>perturbée été</u> par un fracas dehors.
50	La star qui visite <u>le musée</u> a des lunettes.	La star qui visite <u>la musée</u> a des lunettes.	La star qui visite <u>musée le</u> a des lunettes.
51	Ils plongèrent dans le lac et rapportèrent <u>la clé</u> au prince.	Ils plongèrent dans le lac et rapportèrent <u>le clé</u> au prince.	Ils plongèrent dans lac le et rapportèrent <u>la clé</u> au prince.
52	Le garçon a donné sa mère <u>une fleur</u> petite et jaune.	Le garçon a donné sa mère <u>un fleur</u> petite et jaune.	Le garçon a donné <u>mère sa</u> une fleur petite et jaune.

53	Le patient a peur que <u>le traitement</u> sera pénible.	Le patient a peur que <u>la traitement</u> sera pénible.	Le patient a peur que <u>traitement le</u> sera pénible.
54	Le touriste a été fasciné par <u>le monument</u> mal-situé.	Le touriste a été fasciné par <u>la monument</u> mal-situé.	Le touriste a été fasciné par <u>monument le</u> mal-situé.
55	Il pensa qu'elle serait bientôt <u>la victime</u> des bêtes sauvages.	Il pensa qu'elle serait bientôt <u>le victime</u> des bêtes sauvages.	Il pensa qu'elle serait bientôt <u>victime la</u> des bêtes sauvages.
56	Une reine était assise à <u>sa fenêtre</u> un jour de plein hiver.	Une reine était assise à <u>son fenêtre</u> un jour de plein hiver.	Une reine était assise à <u>fenêtre sa</u> un jour de plein hiver.
57	Un jour ma petite soeur a fait <u>une chose</u> terrible.	Un jour ma petite soeur a fait <u>un chose</u> terrible.	Un jour ma <u>soeur petite</u> a fait une chose terrible.
58	Tu m'as envoyé <u>une lettre</u> par la poste.	Tu m'as envoyé <u>un lettre</u> par la poste.	Tu m'as envoyé <u>lettre une</u> par la poste.
59	Le pain a <u>un goût</u> de romarin et l'ail.	Le pain a <u>une goût</u> de romarin et l'ail.	Le pain a <u>goût un</u> de romarin et l'ail.
60	Le combattant qui admire <u>le courage</u> a des médailles.	Le combattant qui admire <u>la courage</u> a des médailles.	Le combattant qui admire <u>courage le</u> a des médailles.
61	Vous devez être prudent parce que <u>la glace</u> est glissante	Vous devez être prudent parce que <u>le glace</u> est glissante.	Vous devez être prudent parce que <u>glace la</u> est glissante.
62	Le garçon a allumé <u>un feu</u> pour se tenir chaud.	Le garçon a allumé <u>une feu</u> pour se tenir chaud.	Le garçon a allumé <u>feu un</u> pour se tenir chaud.
63	Pendant <u>le concert</u> mon frère a bu un café.	Pendant <u>la concert</u> mon frère a bu un café.	Pendant le concert <u>frère mon</u> a bu un café.
64	Le facteur qui peut choisir <u>le stylo</u> a une casquette.	Le facteur qui peut choisir <u>la stylo</u> a une casquette.	Le facteur qui peut choisir <u>stylo le</u> a une casquette.
65	Je vais aller en ville pour boire <u>une tasse</u> de thé.	Je vais aller en ville pour boire <u>un tasse</u> de thé.	Je vais aller en ville pour boire <u>tasse une</u> de thé.
66	J'avais demandé et obtenu <u>la</u>	J'avais demandé et obtenu <u>le</u>	J'avais demandé et obtenu

	<u>permission</u> de faire des expériences	<u>permission</u> de faire des expériences.	<u>permission la</u> de faire des expériences.
67	Le spectateur qui adore <u>la pièce</u> est très ému.	Le spectateur qui adore <u>le pièce</u> est très ému.	Le spectateur qui adore <u>pièce la</u> est très ému.
68	Ça change d'<u>un liquide</u> à un solide.	Ça change d'<u>une liquide</u> à un solide.	Ça change d'un <u>à liquide</u> un solide.
69	La jeune fille a pris <u>un plat</u> de biscuits pour sa soeur.	La jeune fille a pris <u>une plat</u> de biscuits pour sa soeur.	La jeune fille a pris <u>plat un</u> de biscuits pour sa soeur.
70	Le locataire n'était pas heureux avec <u>le prix</u> élevé de l'essence.	Le locataire n'était pas heureux avec <u>la prix</u> élevé de l'essence.	Le locataire n'était <u>heureux pas</u> avec le prix élevé de l'essence.
71	Fidel est devenu <u>un symbole</u> d'un peuple.	Fidel est devenu <u>une symbole</u> d'un peuple.	Fidel est devenu <u>symbole un</u> d'un peuple.
72	Il y a des chaises dans <u>la salle</u> de classe	Il y a des chaises dans <u>le salle</u> de classe.	Il y a des chaises dans <u>salle la</u> de classe
73	Le champion peut être guérir par <u>le médicament</u> très cher.	Le champion peut être guérir par <u>la médicament</u> très cher.	Le champion peut <u>guérir être</u> par le médicament très cher.
74	J'ai une classe <u>le matin</u> chaque vendredi.	J'ai une classe <u>la matin</u> chaque vendredi.	J'ai une classe <u>matin le</u> chaque vendredi.
75	Son père ajoute <u>une étagère</u> avec chaque nouvelle collection.	Son père ajoute <u>un étagère</u> avec chaque nouvelle collection.	Son père ajoute <u>étagère une</u> avec chaque nouvelle collection.
76	La mère a remplit <u>la bouteille</u> avec de l'eau.	La mère a remplit <u>le bouteille</u> avec de l'eau.	La mère a remplit <u>bouteille la</u> avec de l'eau.
77	Quand ils regardent <u>une lumière</u> leurs yeux éclatent.	Quand ils regardent <u>un lumière</u> leurs yeux éclatent.	Quand ils regardent <u>lumière une</u> leurs yeux éclatent.
78	Ils voyagent lentement à travers <u>le désert</u> à dos de chameau.	Ils voyagent lentement à travers <u>la désert</u> à dos de chameau.	Ils voyagent lentement <u>travers à</u> le désert à dos de chameau.
79	Le conducteur a évité <u>le pneu</u> qui a roulé sur la rue.	Le conducteur a évité <u>la pneu</u> qui a roulé sur la rue.	Le conducteur <u>évité a</u> le pneu qui a roulé sur la rue.

80	Il n'y a pas un nuage dans <u>le ciel</u> cet après-midi.	Il n'y a pas un nuage dans <u>la ciel</u> cet après-midi.	Il n'y a pas un nuage dans <u>ciel le</u> cet après-midi.
81	Je dois passer un dernier examen dans <u>mon cours</u> de français.	Je dois passer un dernier examen dans <u>ma cours</u> de français.	Je dois passer un <u>dernier dans</u> examen mon cours de français.
82	Nous descendons à la lueur d'<u>un rayon</u> de lune.	Nous descendons à la lueur d'<u>une rayon</u> de lune.	Nous descendons à la <u>d'un lueur</u> rayon de lune.
83	Maurice se balade <u>la nuit</u> dans les couloirs.	Maurice se balade <u>le nuit</u> dans les couloirs.	Maurice se balade <u>la dans</u> nuit les couloirs.
84	Le magicien qui peut lancer <u>la balle</u> est très prétentieux	Le magicien qui peut lancer <u>le balle</u> est très prétentieux	Le magicien qui peut lancer <u>balle la</u> est très prétentieux
85	Le canard dort dans <u>la tente</u> ouverte.	Le canard dort dans <u>le tente</u> ouverte.	Le canard <u>dans dort</u> la tente ouverte.
86	Dans ce zoo vivait <u>un éléphant</u> qui s'appelait Rosa.	Dans ce zoo vivait <u>une éléphant</u> qui s'appelait Rosa.	Dans ce zoo vivait <u>éléphant un</u> qui s'appelait Rosa.
87	Quand je fais <u>un effort</u> je réussis toujours.	Quand je fais <u>une effort</u> je réussis toujours.	Quand je fais un effort <u>réussis je</u> toujours.
88	J'ai joué <u>une chanson</u> magique.	J'ai joué <u>un chanson</u> magique.	J'ai joué <u>chanson une</u> magique.
89	Jojo était pensif sur <u>le chemin</u> de l'école.	Jojo était pensif sur <u>la chemin</u> de l'école.	Jojo était pensif sur <u>chemin le</u> de l'école.
90	Tu vas acheter <u>une télévision</u> avec ton père.	Tu vas acheter <u>un télévision</u> avec ton père.	Tu vas acheter <u>télévision une</u> avec ton père.
91	Devant la boucherie ça sent <u>le poulet</u> rôti.	Devant la boucherie ça sent <u>la poulet</u> rôti.	Devant la boucherie <u>sent ça</u> le poulet rôti.
92	Pendant <u>une heure</u> il a mangé du gâteau.	Pendant <u>un heure</u> il a mangé du gâteau.	Pendant une heure il <u>mangé a</u> du gâteau.
93	Les parents ont organisé <u>une fête</u> pour leur fille.	Les parents ont organisé <u>un fête</u> pour leur fille.	Les parents ont organisé <u>fête une</u> pour leur fille.

94	Sous un arbre elle vit <u>un massif</u> de fraises.	Sous une arbre elle vit <u>un massif</u> de fraises.	Sous un arbre elle vit <u>massif un</u> de fraises.
95	Un soir sur quatre c'est Aline qui assure <u>la surveillance</u> des tentes.	Un soir sur quatre c'est Aline qui assure <u>le surveillance</u> des tentes.	Un soir sur quatre c'est Aline <u>assure qui</u> la surveillance des tentes.
96	Le bébé a été bercé par <u>le son</u> de la voix de sa mère.	Le bébé a été bercé par <u>la son</u> de la voix de sa mère.	Le bébé a été bercé par <u>son le</u> de la voix de sa mère.
97	Il a retourné <u>le livre</u> a la bibliothèque.	Il a retourné <u>la livre</u> a la bibliothèque.	Il a retourné <u>livre le</u> a la bibliothèque.
98	Pour gérer <u>la publicité</u> on a choisi Patrick.	Pour gérer <u>le publicité</u> on a choisi Patrick.	Pour gérer <u>publicité la</u> on a choisi Patrick.
99	Ils cherchaient dans <u>la montagne</u> de l'or et des diamants.	Ils cherchaient dans <u>le montagne</u> de l'or et des diamants.	Ils cherchaient <u>la dans</u> montagne de l'or et des diamants.
100	Vous devez attendre <u>une seconde</u> avant d'entrer dans la salle.	Vous devez attendre <u>un seconde</u> avant d'entrer dans la salle.	Vous devez attendre une <u>avant seconde</u> d'entrer dans la salle.
101	Une fois arrivée elle cherche <u>le quai</u> du train.	Une fois arrivée elle cherche <u>la quai</u> du train.	Une fois arrivée elle <u>le cherche</u> quai du train.
102	Le directeur qui déteste <u>la mer</u> a la nausée.	Le directeur qui déteste <u>le mer</u> a la nausée.	Le directeur <u>déteste qui</u> la mer a la nausée.
103	La fille a porté <u>la boîte</u> avec l'aide de son ami.	La fille a porté <u>le boîte</u> avec l'aide de son ami.	La fille <u>la porté</u> boîte avec l'aide de son ami.
104	Elle entraîna le général à l'intérieur d'<u>une grotte</u> en haut de la montagne.	Elle entraîna le général à l'intérieur d'<u>une grotte</u> en haut de la montagne.	Elle entraîna le général à l'intérieur <u>grotte d'une</u> en haut de la montagne.
105	Pour aller dans <u>la chambre</u> il monta les escaliers.	Pour aller dans <u>le chambre</u> il monta les escaliers.	Pour aller dans <u>chambre la</u> il monta les escaliers.
106	Il demanda de l'eau et trempa <u>son mouchoir</u> dans cette eau.	Il demanda de l'eau et trempa <u>sa mouchoir</u> dans cette eau.	Il demanda de l'eau et trempa <u>mouchoir son</u> dans cette eau.

107	L'histoire raconte les aventures à travers <u>le temps</u> et l'espace.	L'histoire raconte les aventures à travers <u>la temps</u> et l'espace.	L'histoire raconte <u>aventures les</u> à travers le temps et l'espace.
108	Le coiffeur a utilisé <u>un peigne</u> sur le client.	Le coiffeur a utilisé <u>une peigne</u> sur le client.	Le coiffeur a utilisé <u>peigne un</u> sur le client.
109	Madame Pétesèque prend <u>sa retraite</u> un an plus tard.	Madame Pétesèque prend <u>son retraite</u> un an plus tard.	Madame Pétesèque prend <u>retraite sa</u> un an plus tard.
110	Il reprenait <u>la route</u> chaque matin.	Il reprenait <u>le route</u> chaque matin.	Il reprenait <u>route la</u> chaque matin.
111	La neige était partout dans <u>le jardin</u> hier.	La neige était partout dans <u>la jardin</u> hier.	La neige était partout dans <u>jardin le</u> hier.
112	Le menuisier qui peut construire <u>le fauteuil</u> est très maladroit.	Le menuisier qui peut construire <u>la fauteuil</u> est très maladroit.	Le menuisier qui peut construire <u>fauteuil le</u> est très maladroit.
113	Il portait un chapeau qui couvrait <u>son visage</u> sur la tête.	Il portait un chapeau qui couvrait <u>sa visage</u> sur la tête.	Il portait un chapeau qui couvrait <u>visage son</u> sur la tête.
114	L'homme est allé au dentiste parce que <u>sa dent</u> fait mal.	L'homme est allé au dentiste parce que <u>son dent</u> fait mal.	L'homme est allé <u>dentiste au</u> parce que sa dent fait mal.
115	Philippe donne des concerts à travers <u>le monde</u> depuis qu'il a six ans.	Philippe donne des concerts à travers <u>la monde</u> depuis qu'il a six ans.	Philippe donne des concerts à travers <u>monde le</u> depuis qu'il a six ans.
116	Il y a deux jours avant que je passe <u>un mois</u> au Canada.	Il y a deux jours avant que je passe <u>une mois</u> au Canada.	Il y a deux jours avant que je passe <u>mois un</u> au Canada.
117	Le garçon a reçu <u>un bonbon</u> pour bien se comporter.	Le garçon a reçu <u>une bonbon</u> pour bien se comporter.	Le garçon a reçu un <u>pour bonbon</u> bien se comporter.
118	Il était difficile de déterminer <u>la couleur</u> originale.	Il était difficile de déterminer <u>le couleur</u> originale.	Il était difficile <u>déterminer de</u> la couleur originale.
119	Le train passe par <u>la ville</u> et entre le tunnel.	Le train passe par <u>le ville</u> et entre le tunnel.	Le train passe par <u>ville la</u> et entre le tunnel.
120	Une maman canard était assise	Une maman canard était assise	Une maman canard <u>assise était</u>

sur <u>un nid</u> près du lac.	sur <u>une nid</u> près du lac.	sur un nid près du lac.

Appendix D – Chapter 3 experimental items

Word	
Mandarin	English
身体	Body
酒店	Hotel
母亲	Mother
音乐	Music
病人	Patient
研究	Research
学生	Student
目标	Target
老师	Teacher
婚姻	Marriage
女人	Woman
警察	Police
照片	Picture
聚会	Party
咖啡	Coffee
人们	People
决定	Decide
国家	Nation
放松	Relax
礼物	Gift
结束	Finish

讨论	Discuss
想法	Idea
来到	Arrive
学习	Study
晚餐	Dinner
演出	Perform
父亲	Father
学院	College
故事	Story
歌手	Singer
黑暗	Darkness
窗户	Window
婴儿	Baby
司机	Driver
厨房	Kitchen
机场	Airport
桌子	Table
机器	Machine
邻居	Neighbour

Appendix E - Ethical approval for the ERP experiment reported in Chapter 2

Western Research

Research Ethics

Use of Human Participants - Initial Ethics Approval Notice

Principal Investigator: Prof. Marc Joanisse
File Number: 104721
Review Level: Delegated
Protocol Title: Differences in language processing between native and second language speakers of French: An ERP study
Department & Institution: Social Science\Psychology, Western University
Sponsor: Natural Sciences and Engineering Research Council

Ethics Approval Date: January 30, 2014 **Expiry Date:** December 01, 2015

Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Instruments	Handedness Questionnaire	2013/11/20
Instruments	Language history questionnaire	2013/11/20
Instruments	Example stimuli	2013/11/20
Western University Protocol		2013/12/11
Instruments	French sentences	2014/01/08
Other	Instructions for Mechanical Turk workers.	2014/01/08
Revised Letter of Information & Consent	The letter of information for those recruited via posters with tracked changes.	2013/11/20
Recruitment Items	Recruitment poster	2014/01/06
Instruments	This is an example of the date of birth (DOB) collection. Participants will be asked for their DOB after giving written informed consent to participate. Participants DOB will not be collected with their name but with their unique ID code.	2014/01/01
Other	Debriefing Form	
Letter of Information & Consent	MTurk	

This is to notify you that The University of Western Ontario Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the applicable laws and regulations of Ontario has granted approval to the above named research study on the approval date noted above.

This approval shall remain valid until the expiry date noted above assuming timely and acceptable responses to the NMREB's periodic requests for surveillance and monitoring information.

Members of the NMREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussions related to, nor vote on, such studies when they are presented to the NMREB.

The Chair of the NMREB is Dr. Riley Hinson. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Ethics Officer to Contact for Further Information

Grace Kelly (grace.kelly@uwo.ca)	Vikki Tran (vikki.tran@uwo.ca)	Mina Mekhail (mmekhail@uwo.ca)	Erika Basile (ebasile@uwo.ca)

This is an official document. Please retain the original in your files.

Western University, Research, Support Services Bldg., Rm. 5150
London, ON, Canada N6A 3K7 t. 519.661.3036 f. 519.850.2466 www.uwo.ca/research/services/ethics

Appendix F - Ethical approval for the ERP experiment reported in Chapter 3 and 4

《北京师范大学认知神经科学与学习国家重点实验室脑成像中心FMRI实验申请》
专 家 评 审 意 见 表 (V2.0)

课题编号： ICBIR_D_0083_Marc F Joanisse   课题名称：fMRI Investigation of Second Language Proficiency and Age of Acquisition in Mandarin and English

申 请 人：Marc F Joanisse   申 请 人 单 位： The Brain and Mind Institute, the University of Western Ontario

---学术委员会评审意见---

该实验设计合理，方案可行。

--- 伦 理 委 员 会 评 审 意 见 ---

该实验符合伦理与人体安全保护要求。

--------------------------------------- 中 心 审 核 意 见 ---------------------------------------

根据学术委员会和伦理委员会评审意见，北京师范大学脑成像中心批准该项实验用机申请，请按用机流程办理实验用机相关手续。

北京师范大学认知神经科学与学习国家重点实验室

北京师范大学认知神经科学与学习国家重点实验室脑成像中心FMRI实验申

Curriculum Vitae

Education:

2017:   PhD Psychology, University of Western Ontario, London, Ontario, Canada. Advisor: Dr. Marc Joanisse.

2013:   MSc Psychology, University of Western Ontario, London, Ontario, Canada. Advisor: Dr. Marc Joanisse.

2010:   BSc (honours) Neuroscience, Dalhousie University, Halifax, Nova Scotia, Canada. Advisor: Dr. Aaron J. Newman.

Honours Awarded:

2016:   Ontario Graduate Scholarship, $15,000

2015:   PSAC Local 610 Academic Achievement Scholarship, $500

2013:   Leola E. Neal Award for Best Master's Thesis, $450

2013:   Natural Sciences and Engineering Research Council of Canada Postgraduate Scholarship, Three-Year Doctoral Scholarship, $63,000

2013:   Ontario Graduate Scholarship, $15,000

2013:   PSAC Local 610 Academic Achievement Scholarship, $500

2012:   Ontario Graduate Scholarship, $15,000

2006:   Dalhousie Entrance Scholarship, $1,500

Professional Experience:

2011-2017:   Teaching Assistant, Department of Psychology, University of Western Ontario.

2015:   FMRI consultant to CBC Marketplace, Toronto, Canada

2011:   ERP technical consultant to Dr. Joël Dickinson, Department of Psychology, Laurentian University, Ontario, Canada.

Peer-Reviewed Publications:

Nichols, E.S. & Joanisse, M.F. (2016). Functional activity and white matter microstructure reveal the independent effects of age of acquisition and proficiency on second-language learning. *NeuroImage*, *143*, 15-25.

Nichols, E.S. & Grahn, J.A. (2016). Neural correlates of audiovisual integration in music reading. *Neuropsychologia, 91*, 199-210.

Newman, A.J., Tremblay, A., **Nichols, E.S.**, Neville, H.J., & Ullman, M.T. (2012). The Influence of Language Proficiency on Brain Activation in Native and Late Learners of English: An ERP study. *Journal of Cognitive Neuroscience, 24*(5), 1205-1223.

Publications Under Review:

Nichols, E.S. & Joanisse, M.F. Individual differences predict ERP signatures of second language learning of novel grammatical rules

Nichols, E.S., Gao, Y., Liu, L., & Joanisse, M.F. Representational dissimilarity of first and second languages in the bilingual brain

Publications In Preparation:

Nichols, E.S., Joanisse, M.F., Gao, Y., & Liu, L. Age of second-language acquisition predicts white matter microstructure in bilinguals

Talks:

Peer-Reviewed:

Nichols, E.S.*, McKinlay, S., Russell, M.L., & Joanisse, M.F. (2016). Effects of proficiency and age of acquisition on grammatical gender processing in second language speakers. Canadian Society for Brain, Behaviour, and Cognitive Science 26th Annual Meeting, Ottawa, Ontario, Canada. June, 2016.

Joanisse, M.F.*, Welcome, S., & **Nichols, E.S.** (2015). Gray- and White-Matter Correlates of Individual Differences in Reading and Second Language Learning. Talk presented at the Canadian Society for Brain, Behaviour, and Cognitive Science 25th Annual Meeting, Ottawa, Ontario, Canada. June, 2015.

Nichols, E.S.* & Joanisse, M. F. (2015). The other side of the tracts: structural connectivity in second language speakers. Talk presented at the Western Interdisciplinary Student Symposium on Language Research, London, Canada. March, 2015.

Joanisse, M. F.* & **Nichols, E.S.** (2013). Lexical processing in second language learners: What do we know? Talk presented at the Twentieth Annual Meeting of the Society for the Scientific Study of Reading, Hong Kong, China. July, 2013.

Newman, A.J.*, Tremblay, A., & **Nichols, E.S.** (2010). Dissociating age of acquisition from fluency: Linear mixed-effects modeling of proficiency and N400 amplitude in native speakers and bilinguals. Talk presented at the Neurobiology of Language Conference, San Diego, USA. November, 2010.

Nichols, E.S.*, Marchand, Y., & Newman, A.J. (2010). Effects of proficiency on morphological priming in second language French learners: An ERP study. Canadian Society for Brain, Behaviour, and Cognitive Science 20th Annual Meeting, Halifax, Canada. June, 2010.

Invited:

Nichols, E.S.* & Joanisse, M.F. (2013). Neural correlates of second language acquisition: Proficiency and age of acquisition in Mandarin-English bilinguals. Beijing Normal University, Beijing, China. July, 2013.

Posters:

Peer-Reviewed:

Nichols., E.S.*, Joanisse, M.F., Gao, Y., & Liu, L. (2017). Multivariate analyses reveal distributed and overlapping neural representations of bilinguals' first and second languages. Cognitive Neuroscience Society, San Francisco, March, 2017.

Nichols, E.S.* & Grahn, J.A. (2015). Audiovisual integration of musical information modulates the P300. Inaugural Brain and Mind Institute Symposium, London, Canada, September 2015.

Nichols, E.S.* & Grahn, J.A. (2015). ERP markers of audiovisual integration in musicians and non-musicians. Society for Music Perception and Cognition, Nashville, USA, August 2015.

Nichols, E.S.*, Joanisse, M.F., & Farmer, T.A. (2014). The downstream consequences of form-to-expectation mismatch. Architectures and Mechanisms for Language Processing, Edinburgh, United Kingdom, September 2014.

Nichols, E.S.* & Joanisse, M.F. (2014). Proficiency and age of acquisition predict brain activation and white matter connectivity in Mandarin-English bilinguals. Society for the Neurobiology of Language. Amsterdam, Netherlands, August, 2014.

Nichols, E.S.* & Joanisse, M.F. (2013). Proficiency and age of acquisition independently modulate brain activity in Mandarin-English bilinguals. The Psychonomic Society 2013 Annual Meeting, Toronto, Canada. November 2013.

Nichols, E.S.* & Joanisse, M.F. (2013). Neural correlates of second language acquisition: Proficiency and age of acquisition in Mandarin-English bilinguals. Canada-Israel Symposium on Brain Plasticity, Learning, and Education, London, Canada. June 2013.

Nichols, E.S.* & Joanisse, M.F. (2013). Do age of acquisition and proficiency independently modulate brain activation in second language speakers? Lake Ontario Visionary Establishment 42nd annual meeting, Niagara Falls, Canada. February, 2013.

Newman, A.J.*, Tremblay, A., & **Nichols, E.S.** (2010). Dissociating age of acquisition from proficiency: On the use of linear mixed-effects modeling of ERP data in native speakers and bilinguals. Donostia Workshop on Neurobilingualism, Donostia-San Sebastian, Spain. October, 2010.

Professional Service:

2016: 1st Annual Inspiring Young Women in STEM conference, Co-organizer, University of Western Ontario

2015-2016: Brain and Mind Institute Steering Committee, Graduate Student Representative

2015-2016:	Co-supervisor to physiology and pharmacology undergraduate honours thesis student Melissa Liu, University of Western Ontario
2015:	Ad Hoc Reviewer, Experimental Brain Research
2015:	Colloquium Committee, Graduate Student Representative
2014:	Co-supervisor to undergraduate honours thesis student Scotia McKinlay, University of Western Ontario
2014:	Colloquium Committee, Graduate Student Representative
2014:	Ad Hoc Reviewer, PLOS ONE
2013:	Co-supervisor to undergraduate honours thesis students Allie Gallinger and Melanie Russell, University of Western Ontario
2013:	Women in Science discussion group, co-founder and coordinator, University of Western Ontario.
2012:	Psychology Graduate Student Association, representative for 2012-2013 academic year, University of Western Ontario.
2012:	Graduate Teaching Assistants' Union Scholarships' Evaluation Committee, Graduate Student Member, University of Western Ontario.
2011:	Psychology Graduate Affairs Committee, Graduate Student Representative, University of Western Ontario.

Professional/Scientific Associations:

Cognitive Neuroscience Society

Society for the Neurobiology of Language

Canadian Society for Brain, Behaviour, and Cognitive Science