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The influence of proficiency and age of acquisition on second language processing: An fMRI study of Mandarin-English bilinguals

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Graduate Program in Psychology
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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THE INFLUENCE OF PROFICIENCY AND AGE OF ACQUISITION ON SECOND LANGUAGE PROCESSING: AN FMRI STUDY OF MANDARIN-ENGLISH BILINGUALS

(Thesis format: Monograph)

by

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Graduate Program in Psychology

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

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Abstract

Research investigating the neural correlates of second language (L2) processing has usually studied age of acquisition (AoA) and proficiency separately. Presently, we examined both in parallel, treated as continuous variables. We used fMRI to study neural activity for L2 processing in adult native Mandarin speakers who are L2 English speakers. Behavioral measures of language proficiency and AoA were obtained from subjects prior to performing a picture-word matching task during an fMRI scan. Brain activity during L2 English processing was shown to be independently affected by AoA and proficiency; activity in left superior temporal gyrus and right parahippocampal gyrus was modulated by AoA when L2 proficiency was accounted for, while activity in right insula, right middle temporal gyrus, and left parahippocampal gyrus was modulated by L2 proficiency regardless of AoA. These results suggest that brain organization of L2 lexico-semantic processing is susceptible to L2 ability levels as well as age-dependent learning.

Keywords

Language, second language, bilingualism, fMRI, proficiency, age of acquisition

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The influence of proficiency and age of acquisition on second language processing: An fMRI study of Mandarin-English bilinguals

The experience of learning a second language (L2) tends to differ between adults and children. While children acquire an L2 almost as easily as their first language (L1), adult L2 learners must work much harder and often do not attain native-like proficiency, which is skill and facility in L2. While the effects of age of L2 acquisition (AoA) and proficiency on L2 processing have both been widely studied in the past, it is still unclear how they independently modulate brain activity in L2 speakers. The present study was designed to address this, investigating the neural correlates of proficiency and AoA in Mandarin-English L2 speakers performing a word-object matching task.

Historically, the focus of L2 research has been on AoA. The critical period hypothesis, first proposed by Lenneberg (1967) and adopted to explain age-dependent differences in L2 learning by Johnson and Newport (1989), states that after a certain age, the ability to acquire an L2 is greatly diminished or lost. While it has since been shown that adults can indeed become fluent in an L2, there is appreciable inter-individual variability in the level of proficiency attained, with adults often maintaining a foreign accent and experiencing difficulties especially with the development of grammatically complex sentences (Hakuta, Bialystok & Wiley, 2003; Johnson & Newport, 1989; Wartenburger, 2003; Weber-Fox & Neville, 1996); in contrast, prior to puberty most individuals attain a high L2 proficiency level. In spite of these difficulties, learning an L2 as an adult is not impossible, and many adult learners are able to attain a high degree of proficiency (Nicol & Greth, 2003; Mueller, Hahne, Fujii, & Friederici, 2005).

Knowing that AoA plays a role in L2 ability suggests that there may be maturational constraints affecting the processing of an L2 (Pakulak & Neville, 2011, Weber-Fox & Neville, 1996). However, if L1 and L2 are indeed processed differently regardless of AoA, then it may be that language status (that is, whether it is one's L1 or L2) matters; i.e. if one language is acquired following another, it will not be processed in the same way as the first (Perani et al., 2003; Wang et al., 2011). Conversely, if in some cases, such as with early AoA, the languages are processed similarly, it may be possible that language status does not matter. That is, if a language is acquired early enough in life, it will be processed similarly to all other languages learned early in life. This problem is currently being addressed in the literature, with evidence for both sides (Morgan-Short, Sanz, Steinhauer, & Ullman, 2010; Newman, Tremblay, Nichols, Neville, & Ullman, 2012; Pakulak & Neville, 2011; Perani et al., 2003; Perani et al., 1998; Wang, 2011; Wartenburger et al., 2003).

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, and vice versa. There is still much debate about when, if it exists at all, the critical period ends. Indeed, some researchers suggest that results in support of a critical period are simply confounded with other predictive factors, such as amount of L2 education, chronological age, and L2 language exposure (Flege, Yeni-Komshian, & Liu, 1999). This implies that dividing subjects into two groups of early and late acquisition may not be appropriate, and treating AoA as a continuous variable may allow for a more complete and accurate description of the effects of AoA on L2 processing.

Complicating the interpretation of the AoA literature is the variability in proficiency observed across L2 learners, and the fact that AoA and proficiency level are highly intertwined. Comparing groups with early and late AoAs can be difficult, as proficiency is rarely matched across groups. Early learners typically have a higher level of proficiency than late learners (Stevens, 1999; Wartenburger, 2003), consistent with the critical period hypothesis. However the difference is not absolute, and there is significant variability in proficiency levels in both early and late L2 learners. Proficiency of native (L1) speakers is also rarely measured, and this too might influence groupwise differences. Indeed, prior studies that have assessed this factor found that it is not always matched across L1 and L2 groups (Newman, Tremblay, Nichols, Neville, & Ullman, 2012, Wang et al., 2011). Because AoA and L2 proficiency are correlated, observations initially attributed to AoA may instead be due to level of proficiency. Evidence suggesting that L1 and L2 are processed in a qualitatively different way may in fact be due to differing proficiencies, and it is important to account for both AoA and L2 proficiency when making an argument for either case.

The relationship between proficiency and AoA is complex. The fact that late learners tend to be less proficient than early learners is likely driven in part by the effects of AoA. Learning a language later in life may have effects that lead speakers to have low proficiency. However, there is variability in L2 proficiency levels that cannot be accounted for by AoA. Other factors that may affect ultimate L2 attainment may include socioeconomic status, motivation, L2 language exposure, type of instruction, or others. Therefore, the variability in proficiency level that is attributable to factors other than AoA is what makes up the factor termed “proficiency”, and these effects must be separated from those of AoA. There are likely unavoidable differences between L1 and L2 learning that arise from AoA, however there may also be differences beyond those attributable to AoA. The present goal is to tease apart the neural correlates of each factor.

There are also inconsistencies in how AoA is evaluated throughout the literature. While some studies have considered AoA to be the age of first exposure (Newman, Tremblay, Nichols, Neville, & Ullman, 2012), others have reported AoA as the age at which subjects moved to a country that spoke the L2 being studied (Weber-Fox & Neville, 1996). Additionally, not all past studies evaluating the effects of proficiency have employed an objective measure of proficiency, instead opting for self-report measures (De Diego Balaguer et al., 2005). Others have used grades in language classes (Chee, Tan, & Thiel, 1999), or performance on a language task such as a word-translation test (Perani et al., 1996; Perani et al., 1998, Perani et al., 2003), while the current study used a subset of questions from standardized language proficiency tests. Consistency in the evaluation of proficiency is lacking, and standardized tests in various languages would be a beneficial tool for the L2 processing literature.

Thus, the question remains of whether L1 and L2 can be processed similarly, or if they are processed in an inherently different way, and how AoA and proficiency differentially affect L2 processing. Late learners who do achieve high proficiency appear comparable in language function to proficient native (L1) speakers. For example, highly proficient L2 speakers, regardless of AoA, show an increase in use of discourse markers and conjunctions when compared to individuals with low proficiency (Neary-Sundquist, 2009). Highly proficient late L2 learners have also shown differences in brain activation from that of low proficiency late learners using neuroimaging (Perani et al., 1998; Wartenburger, 2003), suggesting that L1 and L2 may not be processed in the same way.

It is clear, then, that the interpretation of L2 data can be difficult due to the relationship between AoA and proficiency, both at the behavioural level and the neural level. Individuals with early AoAs tend to have a higher level of proficiency, however this is not always the case. It is possible to achieve a high proficiency level after learning an L2 later in life. While highly proficient L2 speakers may perform similarly in their L1 and L2, differences at the neural level have been demonstrated (Pakulak & Neville, 2011; Perani et al., 1998; Perani et al., 2003; Wartenburger et al., 2003). However, past research has not always accounted for varying levels of proficiency and AoA, and it remains unclear which areas are uniquely associated with each.

The practice of separating subjects into groups such as high/low proficiency and early/late acquisition complicates matters further, as proficiency levels and AoAs vary within group, and the cut-off for each group is arbitrarily chosen. Individuals who have a higher proficiency level in the low proficiency group may be closer to the individuals with lower proficiency in the high proficiency group than to other members of the group they have been placed in. As stated above, various studies have used different cutoffs for early and late AoA. This is because there is no clear age at which a language becomes an L2, nor at which point an L2 learner becomes a "late" learner. Additionally, it has been suggested that past studies using behavioural measures of proficiency to demonstrate AoA effects have not controlled for other, more predictive variables that are especially present in late learners (Flege, Yeni-Komshian, & Liu, 1999). The use of fMRI provides an additional, potentially more sensitive measure of the effects of AoA, especially if AoA is treated as a continuous variable.

Theoretical Considerations

Presently there are several broad theories that describe how AoA and proficiency affect L2 processing. The exposure hypothesis states that L1 and L2 are processed in qualitatively different ways. Specifically, if an individual learns a new language after already having learned an L1, it will not be processed in the same way, regardless of how fluent the individual becomes in his or her L2. This theory is supported by research showing that highly proficient L2 speakers show more extensive activation of language areas when compared to native speakers (Perani et al., 2003), as well as more right hemisphere recruitment (Wang et al., 2011).

The second theory claims that L1 and L2s are processed either similarly or differently, as modulated by proficiency and age of acquisition, depending on the task performed. The declarative/procedural (DP) model (Ullman, 2001) supports this theory, suggesting that different aspects of language may be processed differently in L1 and L2, depending on proficiency (Morgan-Short, Sanz, Steinhauer, & Ullman, 2010; Pinker & Ullman, 2002; Ullman, 2004). This model predicts that the processing of semantics in both L1 and L2 relies on declarative memory, and has shared neural bases in the brain. However, due to increased processing costs, different patterns of activity may emerge. In contrast, the processing of grammar in L1 and L2 has different neural bases, at least at later AoAs. In L1, grammar is subserved by procedural memory, which allows rules or sequences to be applied to semantic content, whereas in L2 the speaker has not yet developed this mechanism of procedural memory, and relies instead on declarative memory processes for grammar processing. If the speaker learned the L2 at an early age, grammar processing will shift to rely on procedural memory. However, at later AoAs, such as after late childhood or puberty, grammatical processing relies largely on declarative memory. This implies that at high proficiencies and early AoAs, L2 processing resembles that of a native speaker, but as AoA increases and proficiency decreases, differences in L2 processing increase.

However, not all researchers agree that L1 and L2 rely on different neural mechanisms; the competition model claims that all aspects of L1 and L2 rely on the same neural substrates (MacWhinney, 1987). Studies have been performed that support connectionist-based models of L2 processing, which generally assume that L1 and L2 are processed by the same brain structures, in similar fashions. Indefrey (2006) has suggested that L1 and L2 rely on similar structures, but similar to lexical/semantic processing in the DP model, 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. A similar claim has been put forward by Abutalebi (2008), who proposes that L2 is acquired through structures similar to those in L1. The author suggests that the neural representation of language processing is more extended in L2 speakers, in part due to competition between L1 and L2, and as they become more proficient, processing becomes more automatic and native-like.

These three theories are important to keep in mind when designing an experiment and interpreting L2 processing data. While breaking subjects into groups of high and low proficiency and early and late AoA will allow the examination of the neural correlates of L2 processing in these groups, it fails to provide a complete picture of the individual effects of each factor and how they modulate brain activity in a continuous fashion. The use of a monolingual native speaking group is beneficial as well; by using native speakers, it is possible to take into account language-specific effects, and it provides the means to compare L2 speakers to native speakers of that language. For example, it would allow the comparison of L2 English speakers to L1 English speakers, in order to determine how English processing differs between L1 and L2. Much of the past literature has performed within-group L2/L1 comparisons, and while also informative, there may be language-specific processing differences that are being attributed to proficiency and AoA, which can be avoided by using a native-speaker group. Thus, by treating proficiency and AoA as continuous measures, and using a native speaker group for comparisons, the data can more accurately describe how L2 processing occurs, and whether it is processed in the same or a different way as L1, both within subject with two different languages, and between subjects in the same language.

Evidence from ERP and Neuroimaging

The effects of proficiency and AoA on L2 learning and use have been studied extensively in the past, and recently there have been several experiments examining their individual effects using event-related potentials (ERP) and neuroimaging techniques. However, the results have been conflicting, with arguments being made to support both similar and differential L1/L2 processing. Several studies have suggested that L1 and L2 are processed differently. Pakulak and Neville (2011) investigated whether AoA affects language processing when proficiency is held constant, using native English speakers and late L2 English speakers matched for proficiency. Subjects performed a phrase structure violation task while having their ERPs recorded. The authors found in the native English group, violations elicited a bilateral anterior negativity ERP component as well as a bilateral P600, both of which have been shown to be sensitive to syntax. In the late learners, however, only a P600 was found, which was larger and longer than that of the native speakers. The authors suggest that these differences are a result of maturational constraints affecting how syntax is processed.

In a similar study by Weber-Fox and Neville (1996), the authors investigated L2 semantic processing by comparing groups of learners with AoAs of 1-3, 4-6, 7-10 and 11-13 years. The experimenters examined the N400 component, which is a negative going ERP component occurring approximately 400 ms post-stimulus, typically in response to semantic violations (Kutas & Hillyard, 1980). They found that the N400 occurred later in only the AoA of 11-13 years group, with no differences between the early and native speakers. Again, these differences were attributed to maturational constraints altering the way L2 is processed in late learners.

The view that L1 and L2 are processed differently has also been supported by functional magnetic resonance imaging (fMRI) studies. Perani and colleagues (2003) found that high proficiency, early acquisition L2 speakers showed more activity in the left inferior frontal gyrus (IFG), left middle frontal gyrus (MFG), left premotor cortex, and left insula during a verbal fluency task in their L2 when compared to their L1. Using magnetoencephalography (MEG), Wang et al. (2011) showed more extensive right-hemisphere activation during a picture-word matching task in high proficiency L2 speakers who acquired English between 8-10 years of age compared to native speakers, again finding processing differences despite high levels of proficiency in L2.

However, there has been evidence to suggest that both L1 and L2 can be processed similarly, depending on the task. Wartenburger and colleagues (2003) performed a detailed study using fMRI to investigate how proficiency and AoA modulate L2 processing, using three groups: High proficiency early AoA, high proficiency late AoA, and low proficiency late AoA. Subjects saw either congruous sentences or sentences with semantic or grammatical violations, in both their L1 and L2. When comparing late and early AoA, the authors found more activity in the bilateral IFG for the grammatical task in late learners, however there were no effects of AoA on semantic processing. When comparing high and low proficiency groups, higher activation was found in the left temporo-parietal junction, right lingual gyrus and right inferior parietal lobe for high proficiency speakers on the grammatical task. For the semantic task, high proficiency speakers showed more activation in the left MFG and right fusiform gyrus, while low proficiency speakers showed more activation in the left IFG and right MFG. From these results, the authors suggest that AoA affects grammar processing more than proficiency does, suggesting that there is either greater activation or less efficient processing in late learners. They also suggest that proficiency affects semantic processing more than AoA does, with the lack of effects of AoA on semantic judgments leading the authors to conclude that semantic processing of L1 and L2 can rely on the same neural substrates at high proficiencies.

A recent meta-analysis by Indefrey (2006) examined 30 fMRI and positron emission tomography (PET) studies of L2 processing. The author found that differential activation for L1 and L2 tended to be driven by late AoA and low proficiency, and the areas of activation differed with task. In addition, it was found that most of the areas showing increased activation were areas also involved in native language processing. Indefrey proposes that these differences can be attributed to efficiency of processing, suggesting that similar areas are involved in processing L1 and L2, with L2 requiring more effortful processing at lower proficiencies.

Rationale for the Current Study

It is clear, then, that the literature is still divided on whether or not L1 and L2 share neural substrates, and the roles that AoA and proficiency play in this regard. While there have been numerous studies aimed to discern how these two factors interact to affect L2 processing, there are none to date that take both into account, while treating each as a continuous variable, in two dissimilar languages. There has also been disagreement between studies about what constitutes early and late learning; mean AoA of late L2 learner groups has ranged from 6 years (Wartenburger, 2003) to 16 years (Abrahamsson, 2012). Similarities between L1 and L2 must also be taken into account. It has been demonstrated that L2 learners may benefit from similarities between languages (De Diego Balaguer, 2005), which may influence processing of L2, especially at lower proficiencies where the speaker may be relying heavily on these similarities. The use of Mandarin/English L2 speakers will prevent knowledge of L1 from being used to process L2, maximally separating the two languages, avoiding any cross-linguistic effects.

The current study employed a picture-word matching task, in which pictures were presented visually simultaneously with auditory words while subjects undergo an fMRI scan. This type of paradigm has been used extensively in language research (Weniger et al., 2000; Desroches, Newman, & Joanisse, 2009; Kuipers & Thierry, 2010). This task involved showing a participant a picture while they simultaneously hear a word, requiring one of two button presses based on whether or not the word and picture match. Using neuroimaging techniques, it is possible to characterize L2 word-processing areas using this task (Wang et al., 2011). Because subjects with a large range of AoAs were recruited, a task was required that is engaging yet not too difficult for low proficiency speakers, to lessen the possibility that differences in the pattern of activation would be due to difficulty with or inability to perform the task. This task also allows for the control of several psycholinguistic factors such as imageability, number of syllables or Chinese characters, and frequency.

With regards to the fMRI data, based on the declarative/procedural model of language (Ullman, 2001) it is expected that as proficiency in L2 increases, the pattern of activity will more closely resemble that of L1 speakers, and at lower proficiencies, the pattern will be more dissimilar. Similarly, it is expected that as AoA decreases, the pattern of activation will more closely resemble that of L1 speakers, and as it increases, there will be greater differences, however the areas affected by AoA are expected to be different from those affected by proficiency. This is expected to be revealed as activity that is predicted by either AoA or proficiency, and the pattern of activation is expected to differ for each variable. Because proficiency is thought to play a larger role in lexico-semantic processing than AoA, it is also predicted that the differential activation will be more extensive for proficiency than for AoA.

Based on prior literature, proficiency is expected to affect processing in the bilateral MFG, the bilateral inferior frontal gyrus (IFG), and the left anterior cingulate. AoA, alternatively, is expected to predict activity in the left posterior IFG (Indefrey, 2006; Wartenburger et al., 2003). It has been suggested that the MFG is involved in a semantic network, and is activated when making semantic decisions. Because the present task relies on making semantic decisions, it is expected that the bilateral MFG will be more active in low-proficiency individuals, who may experience more effortful processing during the task. It has been suggested that the left posterior IFG plays a role in breaking a word into syllables, and additional right-hemisphere posterior IFG may be recruited at lower proficiencies (Indefrey, 2006). Stronger activation in the left posterior IFG has been found in individuals with late AoA, therefore less efficient or automatic syllabic processing may occur in these individuals. Finally, the anterior cingulate has been implicated in attentional task demands as well as error detection, therefore low proficiency individuals are expected to exhibit greater activity in this area due to higher attentional demands and more effortful detection of mismatches.

A key concern is that observed differences between native and L2 ability will not be due to differences in neural representations between languages. Because stimuli will be matched for frequency, imageability, and length, differences observed between groups or within group and between languages should not be due to stimulus-related confounds. To ensure that no stimulus-related effects are interpreted incorrectly, statistical contrasts between L1 English and L1 Mandarin will be performed. This will identify any differences that are specific to the task in each language, indicating that they are not due to differences in L1/L2 processing.

Finally, between-group contrasts in their respective native languages are predicted to reveal differences in activation attributable to language-specific processes. Differences between L1 Mandarin and L1 English processing have been reported (Chee, Tan, & Thiel, 2000), therefore it is important to characterize these differences in the present task to allow for the separation of language-specific differences from differences related to AoA and proficiency.

Methods

Subjects

Subjects consisted of 46 right-handed, neurologically healthy adults, recruited from the London, Ontario community and the University of Western Ontario via posters and word of mouth. Twenty-one (12 females) were monolingual English speakers ranging in age from 18-54 (M = 24, SD = 7.58), and 23 (18 females) were native speakers of Mandarin who were also English L2 speakers, ages 18-35 (M = 22.04, SD = 4.19). L2 speakers learned English between the ages of 4-30 (M = 13.57, SD = 7.06). All subjects had normal hearing and normal or corrected-to-normal vision. Two additional subjects were recruited, one to the monolingual group and the other to the L2 group, but were eliminated from analyses due to equipment failure and an incidental finding (an abnormality in the left temporal lobe), respectively. Subjects were compensated for their time, and total testing time was approximately two hours. This study was approved by the University of Western Ontario Research Ethics Board, and informed consent was obtained from each participant prior to testing.

Behavioural Tasks

Prior to being scanned, all subjects completed a series of proficiency tests and questionnaires. English proficiency was assessed in both groups using a subset of 48 questions from the Test of English as a Foreign Language (ETS, Princeton, NJ; see Appendix A), which consisted of three sections: Grammar, reading comprehension, and vocabulary. L2 speakers completed an additional Mandarin proficiency test, which consisted of a subset of 48 questions from the Hanyu Shuiping Kaoshi (HSK Center, Beijing, China), a standardized test of Mandarin Chinese, again with questions divided into grammar, reading comprehension and vocabulary sections. Order of proficiency test completion was counterbalanced within the L2 speaker group. As opposed to using complete tests, a randomly selected subset of questions in each section of each test was used in order to create a more time-efficient test of proficiency.

AoA of L2 English was determined using a language history questionnaire (Newman, 2008), which determined the age at which subjects first began learning English. Information on socioeconomic status and education was collected using a background questionnaire. Finally, to verify handedness, subjects completed an abridged version of the Edinburgh Handedness Inventory.

L2 speakers completed all behavioural measures in Mandarin aside from the English proficiency test. Letters of information, informed consent and task instructions were likewise provided in Mandarin by a native speaker. English monolinguals completed all measures in English, with all instructions provided by a native English speaker.

fMRI Task and Stimuli

While in the scanner, subjects completed a picture-word matching task. Pictures appeared at 800 x 600 pixels resolution centered on a screen mounted at the head of the scanner bore, which subjects 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) at a comfortable volume for the participant. Subjects were required to indicate with a button press whether the picture and word matched, and were asked to make their response as quickly as possible. Each picture was presented for 2500 ms, and subjects were asked to respond within this time. Stimuli were presented and responses and reaction times were recorded using E-Prime software (Psychology Software Tools, Inc., Sharpsburg, PA) and a Windows laptop.

The imaging session was divided into 8 runs of 20 trials each for a total of 160 trials. A short break was provided between each scanning run. Half of the trial pairs consisted of matching picture-word pairs, and half of the pairs were mismatching pairs. Monolinguals completed all eight runs of English trials, while L2 speakers completed four English runs alternated with four Mandarin runs, with starting language counterbalanced within the L2 speaker group. As shown in Figure 1, each run began with an image reminding subjects which buttons to respond with, and subjects viewed a cross-hair in between trials. Mandarin subjects were also informed of the language in which the next run would be performed. Each trial was 2500 ms duration, with inter-trial interval jittered between 2500 ms - 12,500 ms in 2500 ms increments, allowing us to more accurately deconvolve the blood oxygen level dependent signal.

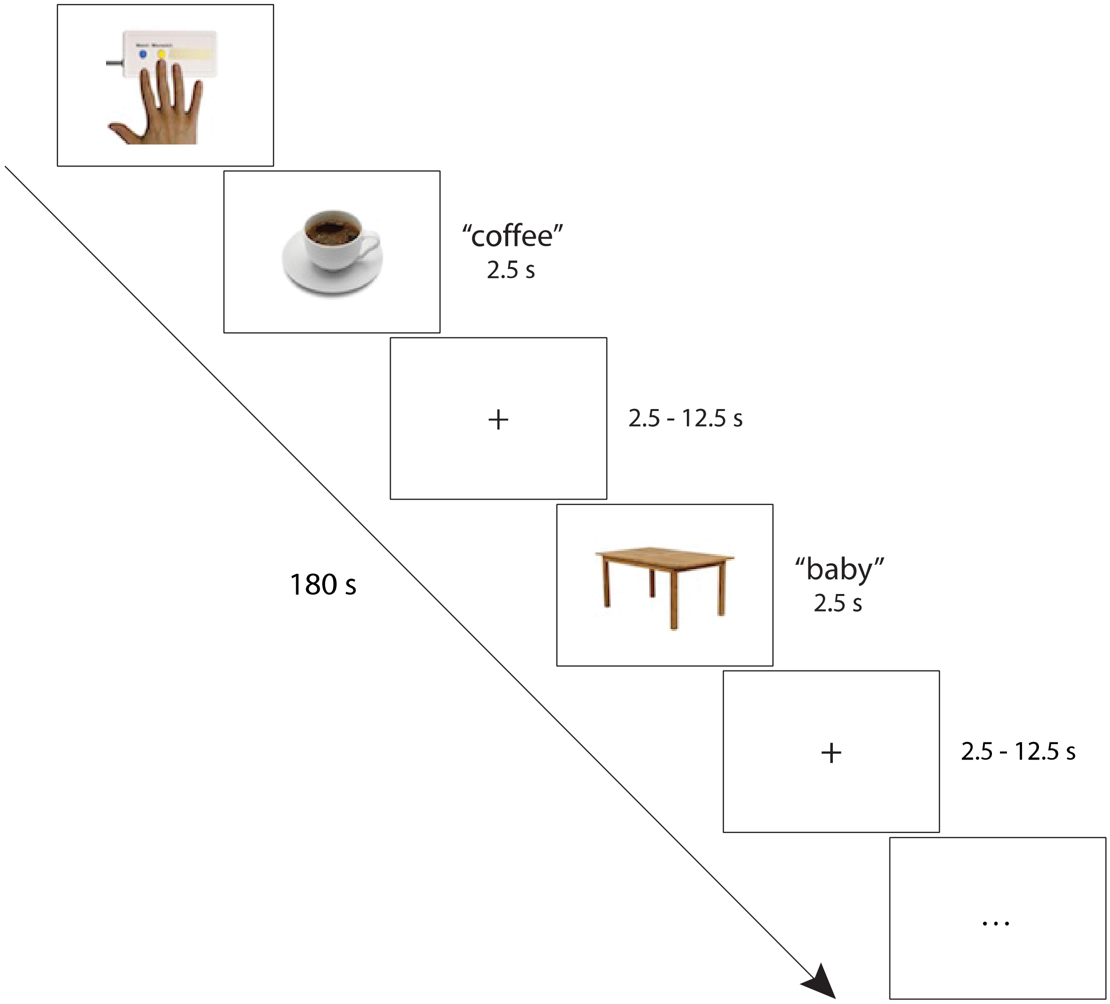

Figure 1. Each run began with an image reminding subjects of which buttons to use. Words did or did not match the pictures. Presentation of stimuli was jittered by multiples of 2.5 s, with the longest ISI being 12.5 s.

Stimuli

There were a total of 40 stimulus words, selected for being common single-word concepts, two-syllables in length in both English and Mandarin, with frequencies greater than 40 per million in both languages (M = 210.35, SD = 241.53). In a pilot study, a list of 65 English words and their Mandarin translations were rated on a seven-point Likert scale for imageability and familiarity (1 being low imageability or familiarity, 7 being high imageability or familiarity) by groups of Mandarin and English native speakers (N= 33 and 42, respectively), and the 40 highest-rated words were used in the present study. Eighty colour photographs were retrieved using Google Image Search, two for each word, and were also rated by native speakers for how well they matched the word they were to represent. The results of this pilot study are summarized in Table 1. None of the measures were significantly different across languages aside from familiarity, which was slightly higher for Mandarin words than English words ($t(39) = 2.17$, $p = .036$).

Table 1. Contrasts of means between languages for frequency, imageability, familiarity, and picture/word match.

Contrasts of word measures between languages

Measure	Mean (SD)		*t*	*p*
	English	Mandarin		
Frequency	210.35 (241.53)	149.60 (132.25)	1.41	.167
Imageability	4.81 (1.20)	5.32 (1.31)	1.82	.076
Familiarity	5.48 (0.66)	5.78 (0.62)	2.17	.036
Picture/word match	6.12 (0.50)	6.20 (0.58)	0.94	.353

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 a transverse plane with 45 slices per volume (TR = 2.5 s; TE = 38 ms; flip angle = 80°; FOV = 192 x 192 mm; voxel size 3 mm^3) using an iPAT parallel acquisition sequence (generalized auto-calibrating partially parallel acquisition [GRAPPA]; acceleration factor = 2), providing full coverage of the cerebrum with partial loss of the cerebellum. A total of 576 functional scans were acquired for each participant over 8 runs (3 min per run). After the last functional run, 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).

Data analysis was performed using the AFNI software package (Cox, 1996). Functional scans were first deobliqued (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 *3dToutcount*, and subsequently removed from statistical analyses using the CENSORTR option in *3dDeconvolve*.

Single-subject statistical maps were formed by creating a general linear model (GLM, AFNI *3dDeconvolve*) for each participant. In monolinguals, six GLM predictors were created as follows: one each for the matching and mismatching trials of odd runs, modeled as a trial-wise impulse function convolved with a canonical hemodynamic response function; one each for the matching and mismatching trials of even runs, one representing the average of absolute motion parameter estimates, and one representing trial-wise reaction times convolved with a canonical hemodynamic response model, which assumed that the blood oxygen level-dependent (BOLD) signal amplitude was modulated by reaction time duration. In L2 speakers, six GLM predictors were created as follows: one each for matching and mismatch trials of English runs, one each for matching and mismatch trials of Mandarin runs, one representing reaction times and one representing motion.

Note that creating the separate GLM parameters for even and odd English trials in the monolingual group allowed the comparison of L2 data from the English runs to that of the matched monolingual data; for example, if the first L2 participant heard English words in the odd runs, then the data from the odd runs in the first monolingual participant would be included when comparing English between the two groups. Including only the odd or even runs also ensured that the same quantity of data was being compared between groups.

Anatomical coregistration was performed by automatically transforming each participant's anatomical scan into standard 3D space (Talairach & Tournoux, 1988) by fitting it to a standard atlas brain using a least-squares cost function (AFNI @*auto_tlrc*). Subjectwise statistical maps were resampled to 1 mm^3, and transformed to stereotaxic space using the parameters obtained for the anatomical transform. A 5 mm FWHM Gaussian blur spatial filter was then applied (AFNI *3dmerge*). Finally, a brain mask was calculated and applied to each subject's GLM using an automatic procedure (AFNI *3dSkullStrip*).

Groupwise statistical contrasts were obtained using independent samples t-tests (AFNI *3dttest*). Correction for multiple comparisons at $p < .05$ was achieved by setting a minimum cluster size of 229.5, obtained using a 10,000 iteration Monte Carlo simulation (AFNI *3dClustSim*) at a voxelwise alpha level of $p < .001$. The first analysis tested for differences in activation between monolinguals and L2 speakers in English, and between groups in their respective L1s (English speakers performing the English task and Mandarin speakers performing the Mandarin task). This was expected to identify regions that show differences in activation between native and L2 speakers of English, thus distinguishing how language status (L1 vs. L2) may affect processing, while comparing across L1 in each language allows inter-language differences in activation to be identified.

A paired samples t-test was similarly performed to identify differences in activation between the L2 group's first and second languages, in order to compare with the regions identified to be differentially involved in the processing of each language. Differences observed when comparing L2 English to L1 Mandarin may be due to language status, or due to differences between the languages themselves. After ruling out language-related areas of activation, areas left over can be attributed to L1/L2 related processing differences.

Subsequent analyses examined the association between subjectwise regional brain activity and behavioral measures obtained prior to scanning as follows. Mean subjectwise GLM Beta estimates were obtained for voxels falling within clusters of significant activation in group statistical maps. These values were then submitted to correlation and regression analyses (AFNI *3dRegAna)* with AoA and L2 proficiency data as covariates or regressors.

Results

Behavioural Results

Figure 2 shows the mean scores on the English and Mandarin proficiency tests by group. The monolingual group and the L2 group performed equally well on the proficiency test in their respective native language (t = 1.17, p = .248), suggesting that the tests were well matched for difficulty across languages. However, monolinguals performed significantly better than the L2 speakers on the English test (t = 7.78, p < .001), and L2 speakers performed significantly better on the Mandarin test than on the English test (t = 3.03, p = .006). Despite past evidence suggesting that proficiency and AoA are highly correlated, no such correlation was found (r = .05, p = .795), suggesting that within the L2 group, proficiency and AoA were unrelated. This may be because Mandarin speakers have minimal opportunity to use English outside of their written curriculum, thus while they begin learning English at an early age, the level of proficiency achieved may not be particularly high.

On the English task, reaction times were significantly faster for monolinguals (M = 991.98 ms, SD = 190.54) than for bilinguals (M = 1152.87 ms, SD = 245.69; t = 2.44, p = .019). In their respective L1s, monolinguals were significantly faster than bilinguals (M = 1280.18, SD = 310.03; t = 3.75, p < .001). There was also a significant difference in reaction time within the bilingual group, with responses being faster on the English task than the Mandarin task (t = 4.39, p < .001).

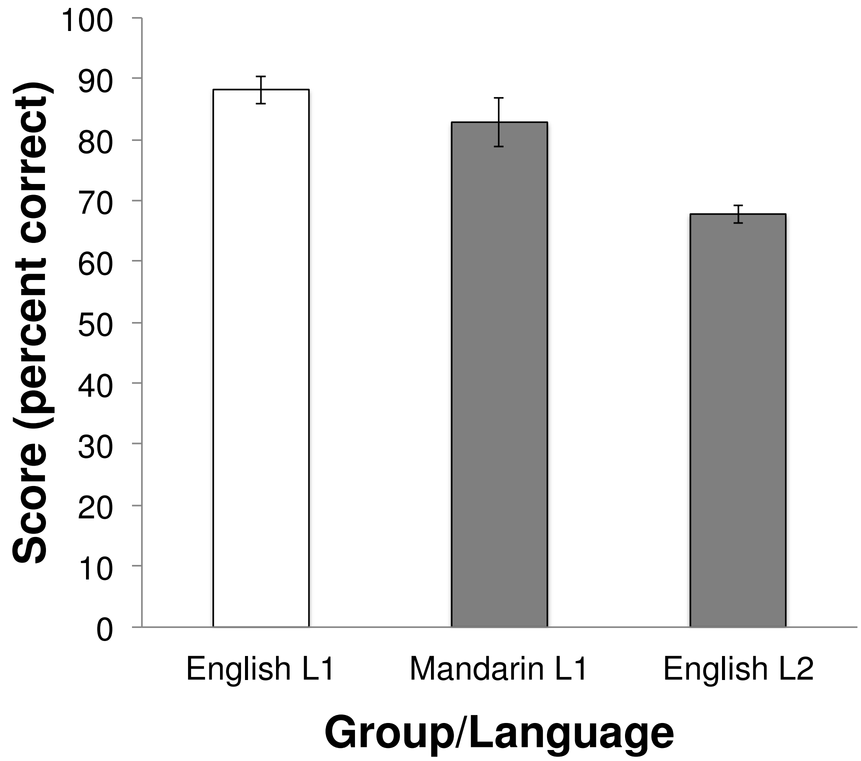

Figure 2. Mean scores on proficiency tests. Error bars denote standard error of the mean.

Response accuracy is depicted in Figure 3. T-tests were performed in order to determine whether the two groups were performing significantly differently on the task. There were no differences in performance between groups on the English runs (i.e., monolingual English vs. second-language English speakers; $t = 1.10$, $p = .277$), nor on the runs in their respective native languages (English L1 vs. Mandarin L1; $t = 1.21$, $p = .233$). The L2 group performed equally well in both languages ($t = .42$, $p = .682$), suggesting that the task was well matched for difficulty across languages.

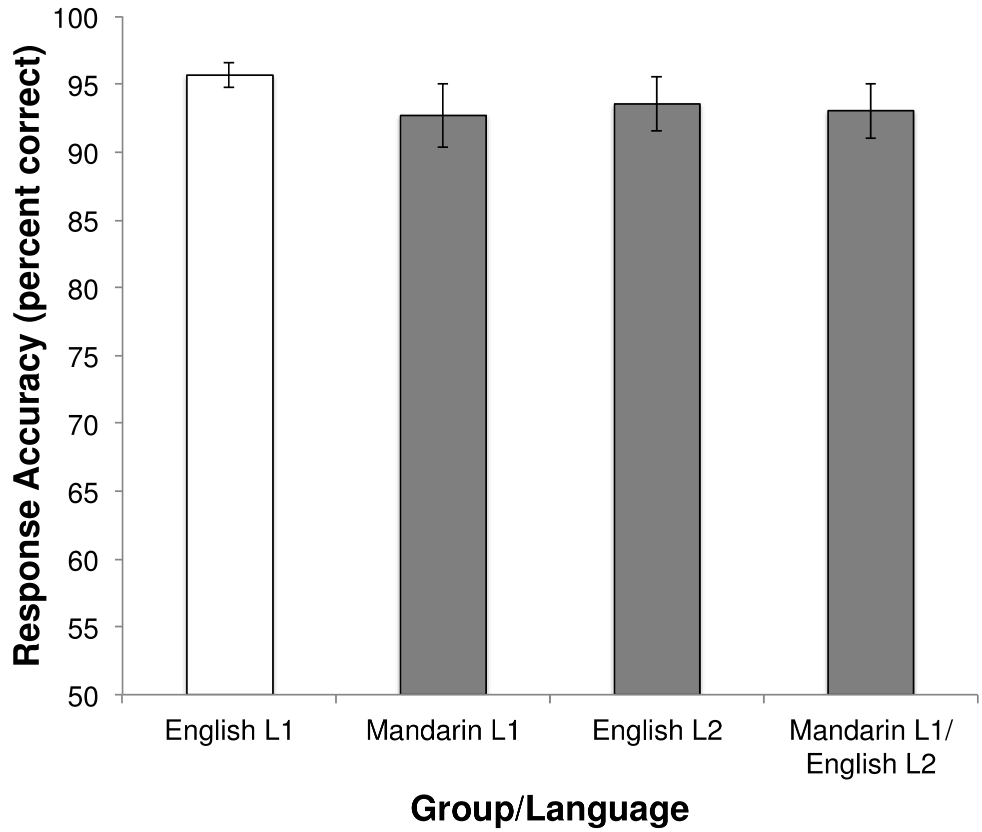

Figure 3. Response accuracy on fMRI task trials. Labels represent the following: English L1, all responses on all trials in the English monolingual group; Mandarin L1, all responses on the Mandarin trials in the bilingual group; English L2, all responses on the English trials in the bilingual group; Mandarin L1/English L2, all responses on all trials in the bilingual group. Error bars denote standard error of the mean.

fMRI Results

L1 Mandarin vs. L1 English

We first performed a between-groups contrast of L1 Mandarin vs. L1 English, which identified brain regions with a significant difference in activation between groups when performing the task in their native language. Because both groups were equally proficient in their first language, and both motion and reaction time were controlled for, this contrast should determine which regions are uniquely involved in lexical processing in either language. The results identified several areas in both the left and right hemispheres were significantly more active for the English group than for the Mandarin group (see Figure 4 and Table 2), with the largest clusters of activation in the bilateral cuneus as well as the right postcentral gyrus. In contrast, there were no regions that were significantly more active for Mandarin L1 versus English L1. A similar between-groups contrast of L1 Mandarin vs. L1 English was performed without controlling for reaction time, which yielded additional areas significantly more active for the Mandarin group than the English group (see Figure 5 and Table 3), namely in the left superior temporal gyrus (STG) and left insula.

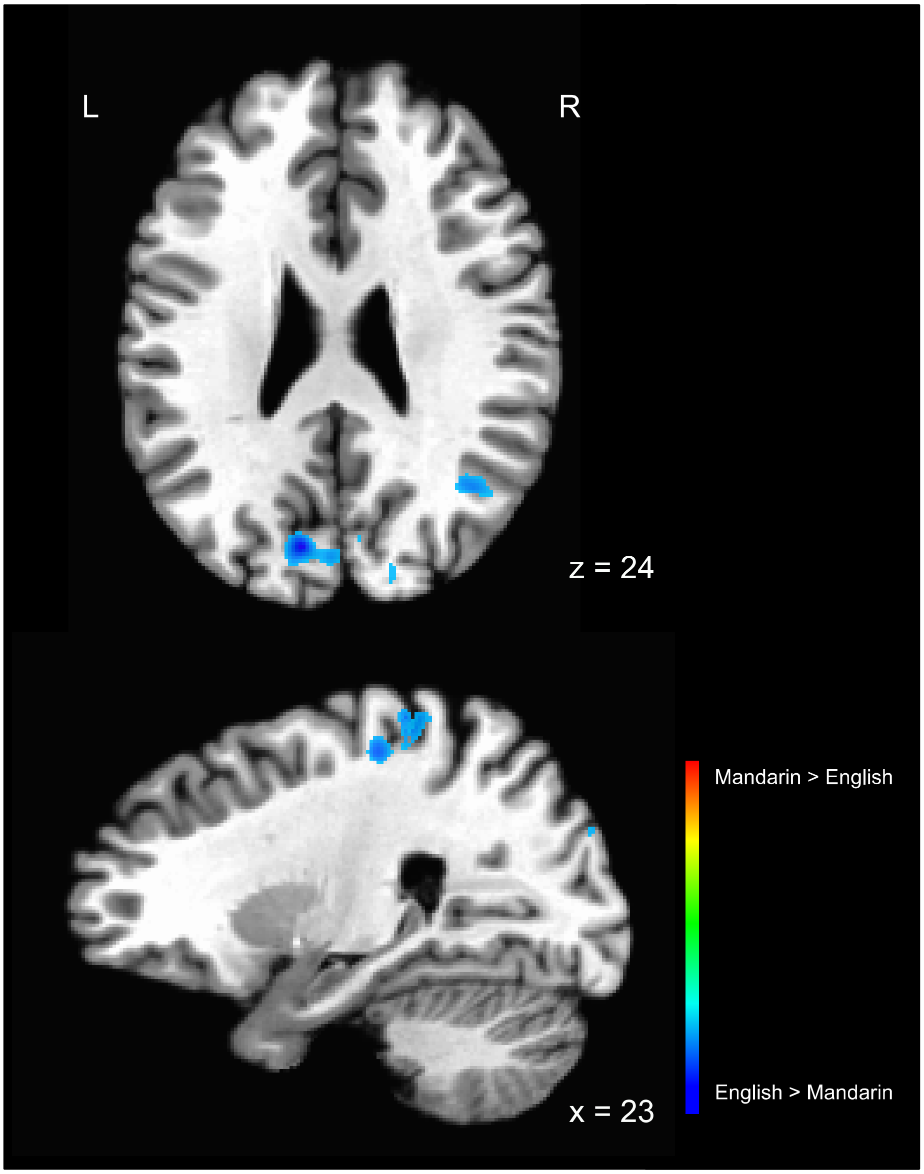

Figure 4. Regions showing more activation for English than Mandarin in the L1 Mandarin – L1 English contrast, at a statistical threshold of $t = 3.539$, $p < .001$. Statistical maps overlaid on the N27 atlas brain. L = left, R = right.

Table 2

Clusters of significant activation in the contrasts between and within groups

Contrast		Region		Talairach coordinates			
Comparison	Activation	L/R	Area	*x*	*y*	*z*	Size (mm^3)
L1 English vs. L1 Mandarin	L1 English > L1 Mandarin	L	Paracentral lobule	0	-45	59	253
		R	Precentral gyrus	43	-15	45	597
		R	Middle temporal gyrus	39	-59	26	416
		R	Postcentral gyrus	23	-25	51	977
		L	Cuneus	-9	-87	35	503
		L	Cuneus	-10	-76	24	1,381
		R	Lingual gyrus	10	-52	4	267
		R	Cuneus	18	-87	33	856
		R	Cuneus	4	-62	5	247
		L	Cerebellum	-12	-67	-32	584
		L	Cerebellum	-29	-72	-29	299
		L	Cerebellum	-14	-46	-4	256
		R	Cerebellum	14	-58	-4	638
L1 English vs. L2 English	L1 English > L2 English	R	Postcentral gyrus	22	-26	51	240
		L	Cuneus	-10	-76	24	454
		R	Cuneus	14	-88	28	446
	L2 English > L1 English	R	Cingulate gyrus	11	10	40	365
L2 English vs. L1 Mandarin	L2 English > L1 Mandarin	L	Superior temporal gyrus	-46	-29	8	1826
		R	Superior temporal gyrus	62	-21	8	360

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

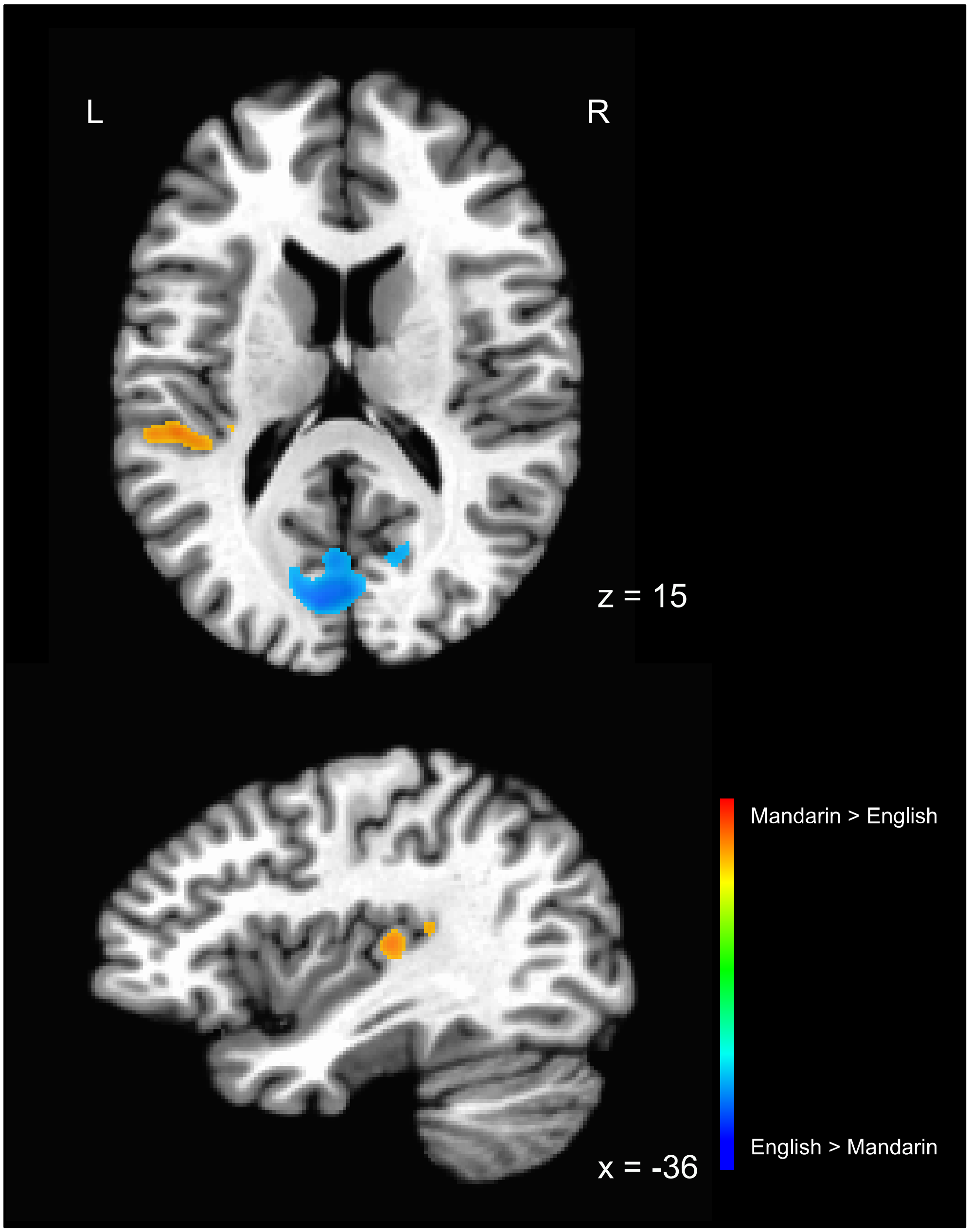

Figure 5. Regions showing more activation for Mandarin than English in the L1 Mandarin – L1 English contrast, without controlling for reaction time, at a statistical threshold of $t = 3.539$, $p < .001$. Statistical maps overlaid on the N27 atlas brain. L = left, R = right.

Table 3

Clusters of Significant Activation in the L1 English vs. L1 Mandarin Contrast, Without Controlling for Reaction Time

Contrast		Region		Talairach coordinates			
Comparison	Activation	L/R	Area	*x*	*y*	*z*	Size (mm^3)
L1 English vs. L1 Mandarin	L1 Mandarin > L1 English	L	Superior temporal gyrus	-45	-31	15	552
		L	Insula	-36	-24	10	416
	L1 English > L1 Mandarin	L	Cuneus	-15	-82	34	381
		R	Cuneus	1	-75	19	4,758
		R	Lingual gyrus	3	-90	-10	851
		R	Posterior cingulate	18	-61	12	354
		R	Cerebellum	48	-39	-29	413
		R	Cerebellum	19	-49	-7	1186

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

L2 English vs. L1 English

The between-subjects L1 English vs. L2 English contrast identified significant differences in activation between groups while performing the task in English. Similar to the L1 Mandarin vs. L1 English contrast above, the bilateral cuneus and right postcentral gyrus were more active in the native English group. However, unlike the previous contrast, the L2 English group showed greater activation in the right cingulate gyrus. This suggests that the increased activity for L1 English speakers in the bilateral cuneus and right postcentral gyrus is likely not task-related, but rather group-related. That is, L1 speakers showed increased activity in these areas both when compared to Mandarin and when compared to L2 speakers of English, suggesting this group may either uniquely recruit these areas, or recruits them to a greater degree than L2 speakers. Activity in the right cingulate gyrus, conversely, appears to be related to L2 processing. As this area was not among the areas shown to be modulated by reaction time in the previous contrast, it is likely related to L2 processing.

Using the data from the L2 English group, multiple linear regression analysis was performed in order to identify brain activity that could be independently explained by AoA and proficiency. Activity in the right posterior cingulate was predicted by AoA when accounting for proficiency (see Figure 6). No areas were predicted by proficiency when accounting for AoA. Partial correlations were then performed in order to determine the strength and direction of the relationship between AoA and the right posterior cingulate while accounting for proficiency. Results indicated a significant positive correlation between activity in the right posterior cingulate and AoA ($r = .77$, $p < .001$), indicating that as AoA increases, activity in the right posterior cingulate also increases.

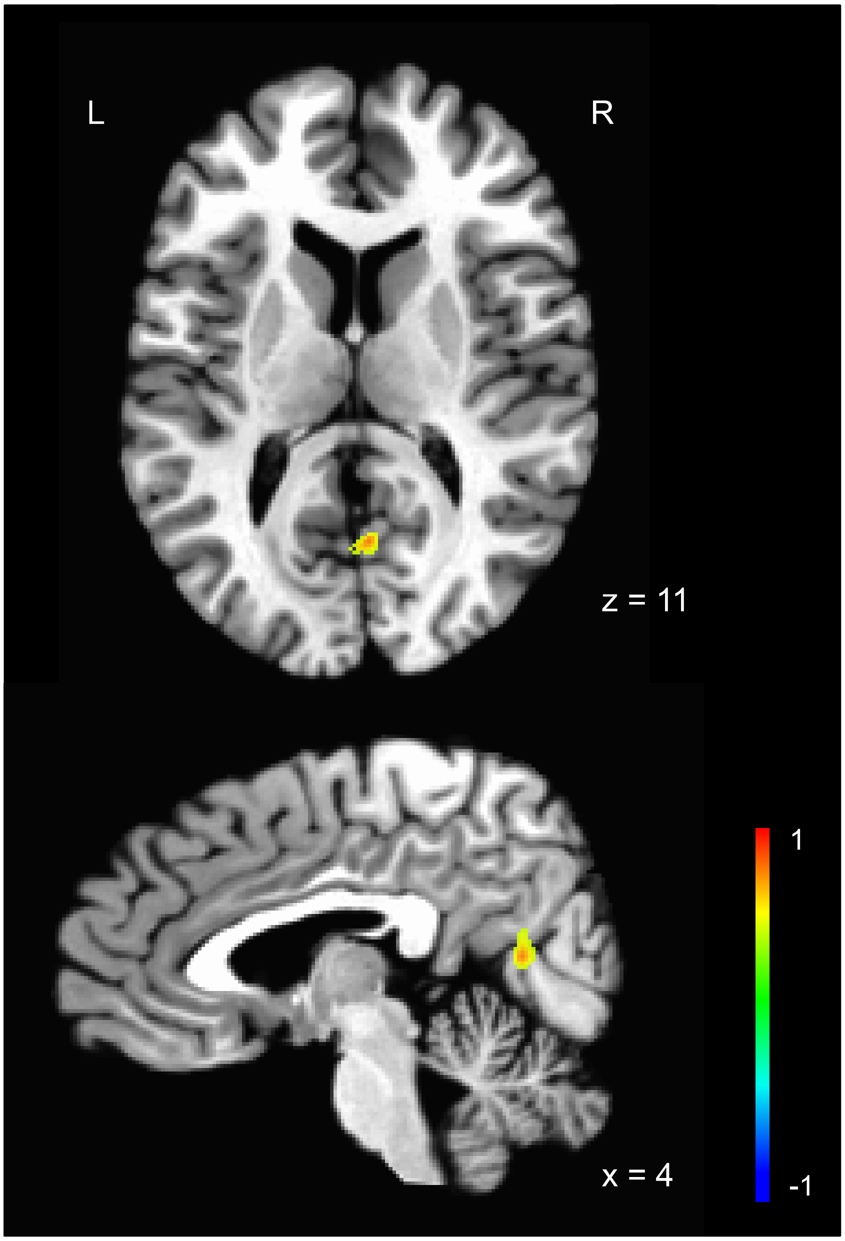

Figure 6. Activation predicted by AoA while taking proficiency into account when comparing L2 English to L1 English, $t = 14.81$, $p = .001$. Statistical maps overlaid on the N27 atlas brain, L = left, R = right.

L1 Mandarin vs. L2 English

Contrasts between the Mandarin and English trials of the L2 group were performed in order to identify areas with a difference in activation within-subjects while performing the lexico-semantic task in their L1 versus L2. Results showed that the bilateral STG was more active in L2 than L1 (see Table 2 and Figure 7). No areas showed more activity for L1 than L2.

Multiple linear regression analysis was next performed using data from the subtraction of Beta values in English trials and Mandarin trials. This was in order to identify areas uniquely activated in L2, whose activation could be explained by the independent effects of either AoA or proficiency. As shown in Table 2, when accounting for proficiency, AoA predicted activity in the left STG and right parahippocampal gyrus (Figure 7), such that activity in these areas increased with increasing AoA in L2 English. When accounting for AoA, proficiency predicted activity in 11 areas, notably the right insula, the right middle temporal gyrus (MTG) and the left parahippocampal gyrus (Table 4, Figure 8), suggesting that activity in these areas increases with increasing proficiency in L2, when compared to L1.

Partial correlations were then performed in order to determine the strength and direction of the relationship of both AoA and proficiency with the regions predicted by each, respectively. Results are summarized in Table 5. Activity in both the left STG and right parahippocampal gyrus was positively correlated with AoA, while activity in all regions predicted by proficiency were positively correlated with proficiency. That is, as AoA increased, so did activity in the left STG and right parahippocampal gyrus; as proficiency increased, so did activity in all 11 areas predicted by proficiency.

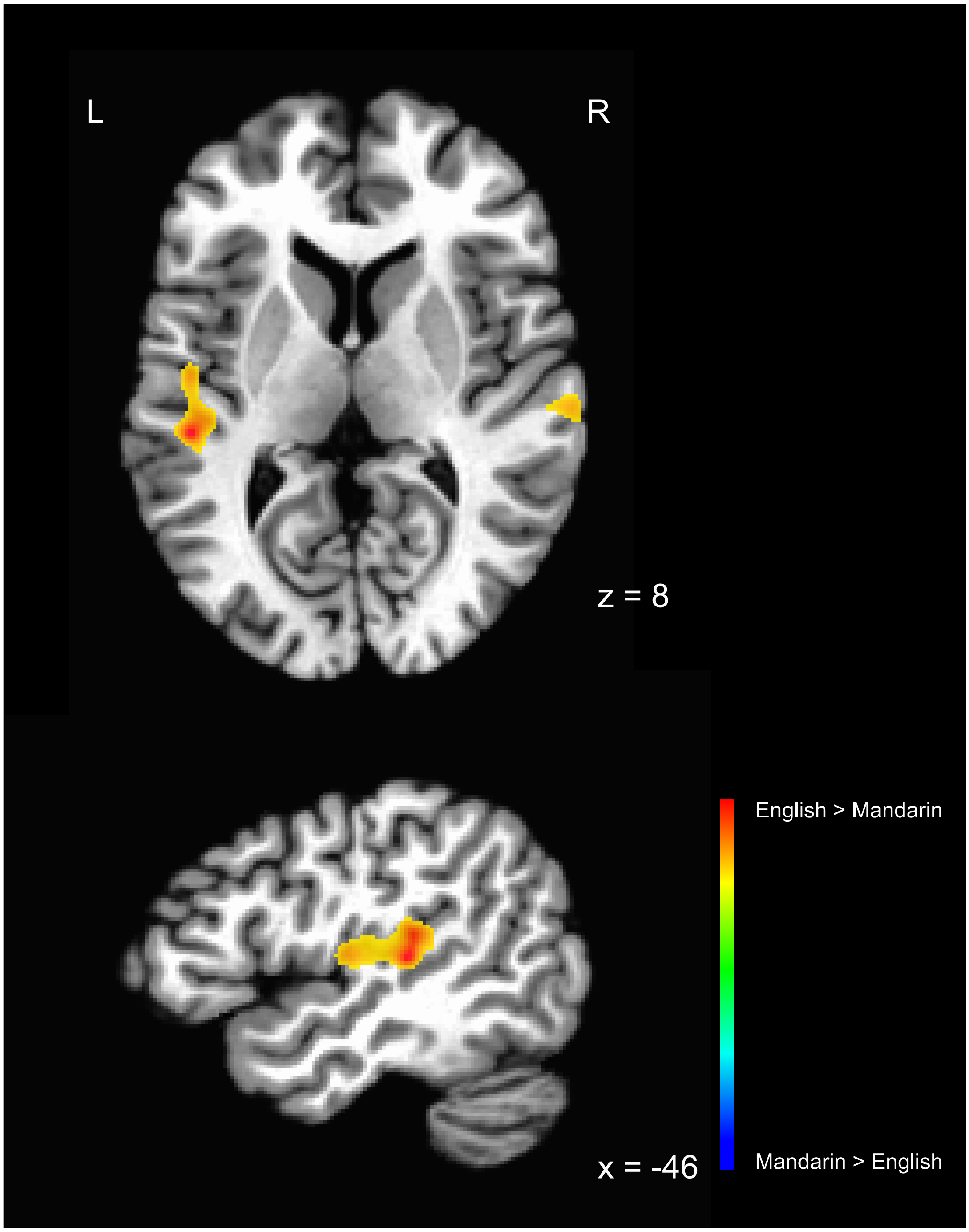

Figure 7. Regions showing more activation for English than Mandarin in the L2 English – L1 Mandarin contrast, at a statistical threshold of $t = 3.786$, $p = .001$. Statistical maps overlaid on the N27 atlas brain. L = left, R = right.

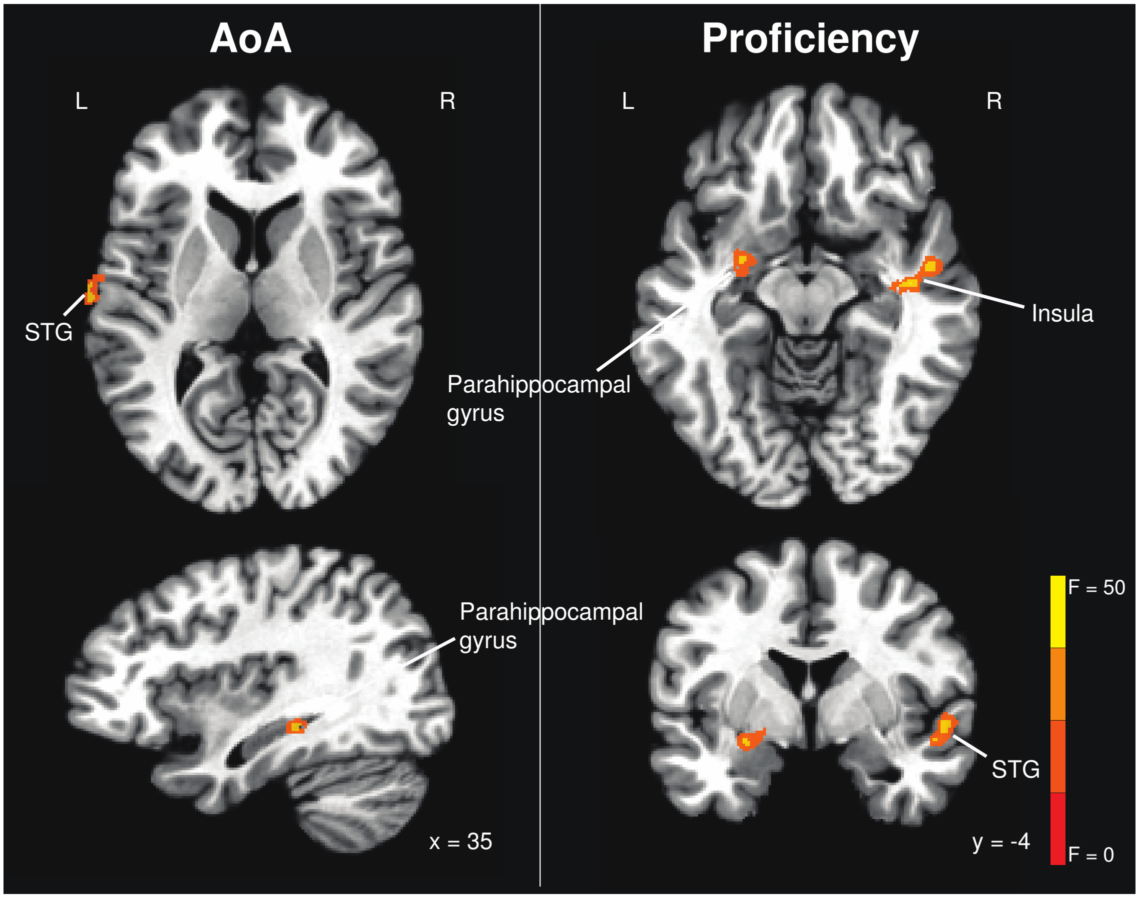

Figure 8. Multiple regression of the difference between L2 English and L1 Mandarin, showing on the left activation correlated with AoA while taking proficiency into account, $F = 14.81$, $p = .001$, and on the right activation correlated with proficiency while taking AoA into account, $F = 14.81$, $p = .001$. Statistical maps overlaid on the N27 atlas brain. L = left, R = right.

Table 4

Clusters of Significant Activation in Multiple Regression of AoA and Proficiency in L2 English When Compared to L1 Mandarin

	Region		Talairach coordinates			
Predictor	L/R	Area	*x*	*y*	*z*	Size (mm^3)
Age of Acquisition	L	Superior temporal gyrus	-64	-14	8	296
	R	Parahippocampal gyrus	35	-30	-8	243
Proficiency	L	Middle temporal gyrus	-37	-60	18	241
	R	Middle temporal gyrus	60	-28	0	697
	R	Superior temporal gyrus	45	-54	15	302
	L	Lingual gyrus	-2	-80	-1	295
	L	Parahippocampal gyrus	-24	-4	-9	498
	R	Insula	41	-13	-9	888
	R	Insula	52	-38	19	265
	L	Cerebellum	-31	-40	-49	781
	L	Cerebellum	-29	-63	-42	540
	R	Cerebellum	28	-46	-51	266
	R	Cerebellum	14	-70	-33	240

Table 5

Partial Correlations of Regions Shown to be Predicted by AoA and Proficiency

	Region			
Predictor	L/R	Area	*r*	*p*
Age of Acquisition	L	Superior temporal gyrus	.81	<.001
	R	Parahippocampal gyrus	.79	<.001
Proficiency	L	Middle temporal gyrus	.76	<.001
	R	Middle temporal gyrus	.76	<.001
	R	Superior temporal gyrus	.74	<.001
	L	Parahippocampal gyrus	.78	<.001
	L	Lingual gyrus	.78	<.001
	R	Insula	.86	<.001
	R	Insula	.80	<.001
	L	Cerebellum	.80	<.001
	L	Cerebellum	.74	<.001
	R	Cerebellum	.77	<.001
	R	Cerebellum	.78	<.001

Discussion

Behavioural results indicated that both the monolingual group and the bilingual group showed equal performance on the proficiency test in their native language. In English, however, monolingual English speakers showed significantly better performance on the English test than did the L2 English group, suggesting that while the groups were matched for proficiency in L1, the monolingual group was significantly more proficient in English than the L2 group. A Pearson correlation indicated that AoA was not significantly correlated with proficiency. Accuracy on the picture-word matching task was the same between monolinguals and L2 speakers, as well as within group on the English and Mandarin runs, indicating that the task was of equal difficulty between languages. However, as discussed below, there was evidence that non-significant group differences did lead to groupwise differences in fMRI activation.

Measures of proficiency and task accuracy were necessary to verify that monolinguals and L2 speakers were matched on L1, that proficiencies varied for L2 in the L2 speaker group, and that both groups were able to complete the fMRI picture-word matching task. Because the proficiency tests indicated that both groups were matched for proficiency in their native language, it is possible to be confident that the L1 contrasts were performed between groups that were matched for L1 ability. Despite the differences in proficiency on the English test between groups, both performed equally on the fMRI picture-word matching task, with the L2 speakers performing equally well on both the Mandarin and English tasks, verifying that group differences could not be due to a general imbalance in the ability to perform the actual behavioral task.

Contrasts between native English and native Mandarin revealed different patterns of activation, with English showing greater bilateral activation in several areas, including the bilateral cuneus and right postcentral gyrus. The results suggest that English either activates a more extensive network of areas, or activates these areas to a greater degree, than does Mandarin. This is important to take into consideration when interpreting within-group comparisons of L1 and L2; processing differences may be related to AoA and proficiency, or to differences inherent to each language.

Because Mandarin and English are so dissimilar, differing in script, tonality, syntax and grammar, it is important to determine whether processing differences exist as well. Even when controlling for nuisance effects of reaction time and movement, this contrast revealed extensive groupwise differences, with all areas of differential activation showing more activity for English than Mandarin. Few studies have investigated the difference between English and Mandarin in native speakers, with most examining the differences between L1 and L2 (Chee, Tan, & Thiel, 1999; Sun, Yang, Desroches, Liu, & Peng, 2011). By assessing the differences between native speakers of either language, it is possible to more accurately interpret the L1/L2 comparison in the L2 speakers, as some differences may be attributable to differences between languages, rather than L1/L2 status. As well, due to the nature of the stimuli, if there are indeed differences between the English and Mandarin tasks, processing differences due to these task differences would be identified using this contrast, and can be accounted for in subsequent analyses. The largest clusters of activation were found in the bilateral cuneus and the right postcentral gyrus. Activity in the cuneus may be related to visual processing, while activity in the right postcentral gyrus is likely related to making a motor response. Both of these differences appear to be task-related rather than language related. However, as discussed below, they only appear in L1 speakers of English, suggesting that these areas are either uniquely recruited or more engaged in English L1 speakers, compared to L2 speakers.

It is also noteworthy that when reaction time was not controlled for, Mandarin showed greater activation than English in the left STG and left insula. The STG has been shown to be involved in the extraction of phonetic information (Chang et al., 2010), therefore the greater involvement of the STG in Mandarin may also be due to the added level of phonetic information carried by tone. This would be tightly correlated with reaction time, as tonal processing may add a level of complexity not present in English, thus modulating reaction time. Activity in the left insula has been related to executive or affective demands of a task, such as perception-action coupling (Sterzer & Kleinschmidt, 2010); this is likely the reason for its involvement here. There may be group-related differences in task demands that are not necessarily of interest. However, it has been suggested that the insula may play a role in processing of affective tone and language content (Ardila, Benson, & Flynn, 1997), and similar to the involvement of the STG, the insula may be related to tonal processing.

Contrasts between groups on the English task (L1 English vs. L2 English) showed greater activation in the bilateral cuneus and postcentral gyrus in L1 English, while L2 English showed more activation in the right cingulate gyrus. Because of the similarity of the pattern of activity in English monolinguals in the present and previous contrast, the greater activation in English monolinguals may indicate areas that are involved in native English processing, which are either not involved in nonnative speakers, or are involved to a lesser degree during L2 lexico-semantic processing. This suggests that these areas may be involved in processing English in native speakers, but may not be recruited as a language processing area in L2 speakers. No activity in either region appeared to be predicted by AoA or proficiency, again suggesting that neither the bilateral cuneus nor the postcentral gyrus is recruited by L2 speakers. The involvement of the right cingulate gyrus in L2 speakers of English, however, suggests that L2 speakers as a group experienced higher attentional demands on the task.

Next, contrasts were performed in order to determine which areas were differentially activated between L1 and L2 within speaker. It is important to determine whether processing differences exist in a single language depending on whether it is being used by an L1 or L2 speaker; however, another view of L2 processing is provided by comparing L1 and L2 within-subject. This contrast reveals areas that are differentially involved in processing two different languages within a single subject. Consistent with previous research, within-group contrasts of L2 and L1 (L2 English vs. L1 Mandarin) revealed that there was greater activation in the bilateral STG when processing L2, which may be due to more effortful processing of L2. The STG is a known area involved in receptive spoken language, therefore it is likely that the activity observed in this region was driven by increased effort in processing L2. No areas were more active in L1 than L2, perhaps due to more ease and efficiency in L1. This effect is also in line with the earlier between-groups comparison of L1 English and L1 Mandarin, in which no areas showed greater activity in Mandarin than English when reaction time was controlled for.

Multiple linear regression analysis using data from the L2 speakers performing the English task revealed that activity in the right posterior cingulate was predicted by L2 AoA, while no activity was predicted by L2 proficiency. Although this is contrary to our predictions, previous research has demonstrated that the posterior cingulate is involved in attention and inhibitory processes (Peterson et al., 1999), and this area may show more activity as AoA increases due to decreased efficiency in suppressing their native language. Surprisingly, there were no areas that were predicted by proficiency in L2 speakers when contrasted with L1 English. This result seems to contradict previous literature, which indicates that lexico-semantic processing may be more influenced by proficiency than AoA (Perani et al., 2003; Wang et al., 2011; Wartenburger et al., 2003). However, most studies compared L1 and L2 within subjects, which may result in language-related differences being attributed to differences in proficiency. Indeed, when comparing across L1 and L2 within subjects, L2 English showed extensive activation that was predicted by proficiency, although few of these areas were those identified to be different in the L1 Mandarin-L1 English contrast. It is also more difficult to obtain statistical significance between-subjects, which also may explain the lack of areas predicted by proficiency.

Multiple linear regression analysis of the L2-L1 contrast revealed differences as to which areas were independently modulated by AoA and proficiency within-subject. AoA uniquely predicted activity in the left STG; partial correlations revealed that as AoA increased, activity in this region also increased, even when proficiency was statistically controlled for. This is not surprising, as the left STG is known to be involved in language comprehension. Therefore it is likely that the increase in activity here is due to less efficient processing as AoA increases. AoA also modulated activity in the right parahippocampal gyrus. Activity in the left parahippocampal gyrus was modulated by proficiency. Partial correlation indicated that as proficiency increased, so did activity in this region. The left parahippocampal gyrus has been implicated in semantic memory and retrieval (Binder et al., 1997), therefore it is likely that this region was involved in the retrieval of semantic information during the picture-word matching task. It is possible that with increasing AoA, due to maturational constraints, right hemisphere areas are recruited for semantic retrieval of L2, which would explain the greater activity in the right parahippocampal gyrus. At early AoA the left parahippocampal gyrus may be used for retrieval of semantic information, however depending on proficiency level, it may be active to different degrees. The increase in this area with increasing proficiency may be due to more appropriate localization of semantic information.

The finding that activity in areas predicted by proficiency showed a positive correlation with proficiency was surprising. These results contradict most of the L2 lexical processing literature, which has typically found a negative correlation between BOLD signal level and proficiency. However, increases in BOLD signal with increased proficiency have been found in other areas, such as with dyslexia. Numerous studies have reported a positive relationship between brain activity and reading level, suggesting that poor readers don't rely on the typical brain regions for reading (Brunswick, McCrory, Price, Frith & Frith, 1999; Seki et al., 2001; Shaywitz et al., 2002). Similarly, L2 speakers with low proficiency may be relying less on the brain regions typically involved in lexico-semantic processing, leading to increased activity in these areas as proficiency increases. The differences in activity found in the areas predicted by proficiency are likely driven by the low proficiency speakers. As proficiency increases, activity increases, reaching a level similar to activation in L1.

The L2 English and the L2-L1 regressions were performed with different aims. The L2 English contrast was performed in order to identify areas that were modulated by L2 proficiency and AoA, including areas that may be similarly active in L1. The L2-L1 regression, in contrast, identified areas that were differentially active in L2 and L1, and determined which of those areas were modulated by L2 proficiency and AoA. The finding that the posterior cingulate was modulated by AoA in the L2 English regression but not in the L2-L1 regression suggests that the efficiency of suppressing another language is modulated by AoA, however it is not specific to suppressing L2. Therefore, it was likely equally involved in suppression of L2 during the L1 task as suppressing L1 during the L2 task, resulting in no differential activation when subtracting L1 from L2.

Theoretical Implications

Overall, the results of the present study indicate that both AoA and proficiency differentially affect L2 processing of lexico-semantic information. In line with previous research, contrasts between and within groups showed different patterns of activation between L1 and L2 speakers of English; however, results of the current study also indicate that each factor modulates activity in different areas, both when considering L2 processing alone, as well as when comparing patterns of activation in L2 to subjects' L1. Thus, it is possible to conclude that as AoA decreases, the patterns of brain activity in native Mandarin speakers when performing a lexico-semantic task in English become more similar to those of their native language. As proficiency increases, the patterns between the L1 and L2 appear to become more similar as well.

These results appear to support the declarative/procedural model, which states that L1 and L2 can be processed similarly if they are learned early enough in life, and at a sufficiently high level of proficiency. Regarding a critical period, these results support previous research stating that languages learned later in life will not be processed similarly to a native speaker. It appears that although the pattern of activation predicted by proficiency becomes more similar to that of a native speaker at high proficiencies, there are still AoA-related differences that are unaffected by level of proficiency. Thus, if an individual learns a language later in life, there will be age-related differences in how that language is processed, compared to both a native speaker, and that individual's native language, regardless of how proficient that individual is in L2.

The present results do not provide support for the exposure hypothesis, as it has been demonstrated that as AoA decreases, the differences in areas modulated by AoA also decrease, suggesting that with early AoA, a speaker will process L2 similarly to L1, when proficiency-related effects are controlled for. The results are also in disagreement with the predictions made by the competition model, which claims that L1 and L2 rely on the same neural substrates, but are modulated by proficiency. As the present results indicate, AoA also modulates L2 processing, suggesting that there are different neural underpinnings between L2s learned early and those learned later in life.

Although the present research provides evidence for differences between L1 and L2 lexico-semantic processing, it is not clear whether similar results would be found in other areas of language such as syntax or sentence processing. Because individual theories make different predictions for syntactic processing than for lexical processing, further research is needed in order to determine which theory best explains L2 language processing. The present approach, in which proficiency and AoA are treated as continuous variables, and the effects of each are independently examined, would permit the testing of the hypotheses of the respective theories for each area of language processing.

The use of two languages that differ in most dimensions also means that these results may not generalize to more similar languages, which may be more likely to rely on similar brain areas, especially if cross-linguistic cues can be used. Sentence processing has been investigated in Spanish-English bilinguals using ERP, while treating proficiency as a continuous variable (Newman, Tremblay, Nichols, Neville, & Ullman, 2012). However, groups of different AoAs were still formed, finding that differences in N400 amplitude were accounted for by proficiency in both native and L2 speakers. Further research examining the neural organization of these effects would benefit the understanding of L2 processing in similar languages.

In this study, as with most others, only one group of L2 speakers was used, therefore it is not possible to observe whether similar areas are involved in L2 learning in English speaking individuals learning Mandarin. From the present study it is only possible to report on the areas modulated by acquiring English as an L2, as opposed to acquiring an L2 in any language. The use of a matched group of English-Mandarin L2 speakers to complement the Mandarin-English L2 group would allow the comparison of the patterns of brain activity between the L2 groups, making it possible to determine whether the pattern of L2 learning is similar regardless of the language being learned.

Conclusions

The present study aimed to investigate the independent effects of proficiency and AoA on L2 single-word processing in Mandarin-English bilinguals. In order to do so, we recruited monolingual English subjects, and Mandarin-English bilingual subjects of varying proficiencies and AoAs, and treated both factors as continuous. After completing a proficiency test in the respective spoken languages, subjects were scanned while completing a picture-word matching task.

Overall, the results of the present study suggest that both AoA and proficiency affect L2 lexico-semantic processing, in different ways. AoA predicted activity in left STG and right parahippocampal gyrus, while proficiency predicted activity in the right insula, right MTG and left parahippocampal gyrus. These results provide a more clear depiction of the areas uniquely affected by AoA and proficiency than previously shown. The current study also provides support for the declarative/procedural model of second language acquisition, in that it appears that L2 single word processing can be similar to that of native speakers if the language is learned early and to a high level of proficiency.

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Appendix A

English Proficiency Test: Subset of Questions from the Test Of English as a Foreign Language (ETS, Princeton, NJ)

Grammar

Prepositional Phrases

1. Surprisingly cost was regarded __________ important factor in choosing a new cell phone by the three teenagers.

(a) as the least
(b) of the least
(c) in the least
(d) to the least

2. Maine's coastline is a major attraction and a vista of sandy beaches contrasted ________ rockbound shoreline.

(a) to the rugged
(b) by the rugged
(c) on the rugged
(d) at the rugged

3. The pressure ________ was intense after his team lost five basketball games in a row.

(a) under the coach
(b) over the coach
(c) of the coach
(d) on the coach

4. In __________, the team has begun to show some form again and has won some big games.

(a) few weeks
(b) few past weeks
(c) the past few weeks
(d) a few weeks since

The Subject

5. In general, ________ have a professional obligation to protect confidential sources of information.

(a) which journalists
(b) journalists
(c) journalists, they
(d) journalists that

6. For ________ you who don't know, "Rainbow" was a credible children's TV show from the 70's and 80's.

(a) those of
(b) those in
(c) these of
(d) these in

7. As was the case throughout the United States, __________ was subject to higher gas prices during the winter of 2002-2003.

(a) for New York
(b) for New York as well
(c) New York which
(d) New York

8. ________ in history caused as much shock and grief worldwide as the 2004 tsunami disaster in Asia.

(a) None natural disaster
(b) That natural disaster
(c) No natural disaster
(d) The natural disaster

Verb Forms

9. That the legal drinking age ________ lowered is a hot topic for debate in many states.

(a) should have
(b) which should
(c) should be
(d) should

10. Discovery of these ancient anthropic markings ________ our understanding of how these early humans interacted with their environment.

(a) has broadened
(b) have broadened
(c) broaden
(d) will have broadened

11. The rivalry between the two communities stems from ancient times and openly __________ to this day.

(a) persist
(b) which persist
(c) persists
(d) which persists

12. Despite the simplicity of their construction, the ancient systems ________ exhibit very complicated behavior.

(a) find to
(b) found to
(c) are found to
(d) were found to

Word Order 1:

13. _________ explores the nature of guilt and responsibility and builds to a remarkable conclusion.

(a) The written beautifully novel
(b) The beautifully written novel
(c) The novel beautifully written
(d) The written novel beautifully

14. Over time the young students will perfect the art of piano playing. After all, such ________ needs delicate handling.

(a) a tuned instrument finely
(b) an instrument tuned finely
(c) a finely instrument tuned
(d) a finely tuned instrument

15. Honore de Balzac said "The errors of ________, from their faith in the good, or their confidence in the true".

(a) women spring, almost always
(b) almost always, women spring
(c) almost women, always spring
(d) almost spring, always women

16. The tenants were asked to throw all recyclable trash into __________.

(a) the green big plastic bag
(b) the big plastic green bag

(c) the big green plastic bag
(d) the green plastic big bag

Reading Comprehension
Reading Passage

1 In 1877, to celebrate the centennial anniversary of America's independence from England, the French government presented the United States with a colossal statue that has come to be one of the most beloved symbols of America. The gift was presented in honor of the alliance between France and America during the Revolutionary War. The formal name of the figure is *Liberty Enlightening the World*, but it is almost universally known as the Statue of Liberty.

2 Since the French government donated the money for the project, French sculptor Frederic-Auguste Bartholdi and engineer Gustav Eiffel were put in charge of the design. The massive structure was assembled in Paris, where it was put on exhibition before being dismantled, then shipped to New York and finally reassembled on Bedloe Island, which was later renamed Liberty Island.

3 The statue is made of thin copper sheets, each just a tenth of an inch thick. They are riveted to an iron framework, which forms the shape of the statue. The statue itself is 151 feet tall, but it stands on top of a large pedestal made of concrete and granite, which was designed by American architect Richard Morris Hunt. The total height of the statue and the pedestal is 305 feet, making it a spectacular sight on the New York City skyline, visible from miles away. The statue holds a torch in one hand, which is meant to symbolize liberty. In the other hand, the figure clutches a book, upon which the date of America's declaration of independence, July 4, 1776, is marked.

4 Due to the difficulty and expense of working on an isolated island, construction took nearly a decade. After the statue was completed in 1886, President Grover Cleveland came to New York to preside over the dedication ceremony. After the unveiling, the Statue of Liberty became a beacon of freedom for both newly arriving immigrants and longtime city dwellers. But after decades of exposure to pollution and harsh ocean air, time had taken its toll on Lady Liberty, as the statue is sometimes called. A full century after the dedication, a restoration effort was launched to repair damage from age and the elements. Funded by both the French and American governments, the renovation of the statue required enclosing it in a scaffold while workers renovated the copper sheeting and replaced the glass torch with a gold one. The newly restored monument was unveiled a few years later, as vibrant and inspiring as ever.

Reading Comprehension

17. Which two countries formed an alliance during the Revolutionary War?
(a) France and Britain
(b) Britain and the United States
(c) France and the United States
(d) Britain and New York

18. Why were French artists responsible for designing the monument?
(a) because the French are the best artists
(b) because the French were funding the project
(c) because America did not want the monument
(d) because France owed money to the American government

19. Look at the word *they* in paragraph 3. What word does *they* refer to?

The statue is made of thin copper sheets, each just a tenth of an inch thick. **They** are riveted to an iron framework, which forms the shape of the statue. The statue itself is 151 feet tall, but it stands on top of a large pedestal made of concrete and granite, which was designed by American architect Richard Morris Hunt. The total height of the statue and the pedestal is 305 feet, making it a spectacular sight on the New York City skyline, visible from miles away.

Answer: ____

20. Look at the word *clutches* in paragraph 3. What word is closest in meaning to *clutches* in paragraph 3?

The statue is made of thin copper sheets, each just a tenth of an inch thick. They are riveted to an iron framework, which forms the shape of the statue. The statue itself is 151 feet tall, but it stands on top of a large pedestal made of concrete and granite, which was designed by American architect Richard Morris Hunt. The total height of the statue and the pedestal is 305 feet, making it a spectacular sight on the New York City skyline, visible for miles around. The statue holds a torch in one hand, which is meant to symbolize liberty. In the other hand, the figure **clutches** a book, upon which the date of America's independence, July 4, 1776, is marked.

Answer: ____

21. Look at the word *one* in paragraph 4. What does *one* refer to?

After the unveiling, the Statue of Liberty became a beacon of freedom for both newly arriving immigrants and longtime city dwellers. But after decades of exposure to pollution and harsh ocean air, time had taken its toll on Lady Liberty, as the statue is sometimes called. A full century after the dedication, a restoration effort was launched to repair damage from age and the elements. Funded by both the French and American governments the renovation of the statue required enclosing it in a scaffold while workers renovated the copper sheeting and replaced the glass torch with a gold **one**.

Answer: ____

22. Look at the word *approximately* in paragraph 4. What word or phrase is closest in meaning to *approximately*?

Due to the difficulty and expense of working on an isolated island, construction took nearly a decade. After it was completed in 1886, President Grover Cleveland came to New York to preside over the dedication ceremony. Several years later, Bedloe Island and nearby Ellis Island became part of a processing center for European Immigrants coming to New York. During the sixty years that the Ellis Island complex was open, it welcomed **approximately** sixteen million people entering America. The site is now the Ellis Island Immigration Museum, and it hosts roughly a million visitors every year.

Answer: ____

23. The following sentence can be inserted into paragraph 4. Circle the number that refers to where the sentence can be inserted.

The copper sheeting of the statue is highly reactive with carbon dioxide from car exhaust and with salty air from the New York Bay.

1 Due to the difficulty and expense of working on an isolated island, construction took nearly a decade. **2** After the statue was completed in 1886, President Grover Cleveland came to New York to preside over the dedication ceremony. **3** After the unveiling, the Statue of Liberty became a beacon of freedom for both newly arriving immigrants and longtime city dwellers. **4** But after decades of exposure to pollution and harsh ocean air, time had taken its toll on Lady Liberty, as the statue is sometimes called. **5** A full century after the dedication, a restoration effort was launched to repair damage from age and the elements. **6** Funded by both the French and American governments, the renovation of the statue required enclosing it in a scaffold while workers renovated the copper sheeting and replaced the glass torch with a gold one. **7**

24. Which of the following is NOT a name by which the monument is called?

(a) Lady Liberty□
(b) Statue of Liberty□
(c) Liberty Island□
(d) Liberty Enlightening the World

Reading Passage

1 Any list of the greatest thinkers in history contains the name of the brilliant physicist Albert Einstein. His theories of relativity led to entirely new ways of thinking about time, space, matter, energy, and gravity. Einstein's work led to such scientific advances as the control of atomic energy, even television as a practical application of Einstein's work.

2 In 1902 Einstein became an examiner in the Swiss patent office at Bern. In 1905, at age 26, he published the first of five major research papers. The first one provided a theory explaining Brownian movement, the zig-zag motion of microscopic particles in suspension. The second paper laid the foundation for the photon, or quantum, theory of light. In it he proposed that light is composed of separate packets of energy, called quanta or photons, that have some of the properties of particles and some of the properties of waves. A third paper contained the "special theory of relativity" which showed that time and motion are relative to the observer, if the speed of light is constant and the natural laws are the same everywhere in the universe. The fourth paper was a mathematical addition to the special theory of relativity. Here Einstein presented his famous formula, E = m(cc), known as the energy mass equivalence. In 1916, Einstein published his general theory of relativity. In it he proposed that gravity is not a force, but a curve in the space-time continuum, created by the presence of mass.

3 Einstein spoke out frequently against nationalism, the exalting of one nation above all others. He opposed war and violence and supported Zionism, the movement to establish a Jewish homeland in Palestine. When the Nazis came to power in 1933, they denounced his ideas. He then moved to the United States. In 1939 Einstein learned that two German chemists had split the uranium atom. Einstein wrote to President Franklin D. Roosevelt warning him that this scientific knowledge could lead to Germany developing an atomic bomb. He suggested the United States begin its own atomic bomb research.

25. Einstein's primary work was in the area of□

(a) chemistry
(b) biology
(c) physics
(d) engineering

26. Which of the following inventions is mentioned in the passage as a practical application of Einstein's discoveries?

(a) Radio□
(b) Automobiles□
(c) Computers□
(d) Television□

27. According to the passage, Einstein supported all of the following except□

(a) the establishment of a Jewish homeland in Palestine
(b) nationalism

(c) atomic bomb research in the United States
(d) the defeat of the Nazis

28. What is "Brownian movement"?
(a) The zig-zag motion of microscopic particles in suspension
(b) The emission of electrons from solids when struck by light
(c) The motion of photons in light
(d) The basis of the theory of relativity

29. Einstein was a citizen of all of the following countries EXCEPT
(a) Belgium
(b) Germany
(c) United States
(d) Switzerland

30. It is clear from the tone of the passage that the author feels
(a) Einstein's work in physics was somewhat tarnished by his conservative political views
(b) Albert Einstein was one of the most brilliant thinkers in history
(c) Einstein's work in physics, though theoretically impressive, led to few practical applications
(d) Einstein's theories have been consistently proven incorrect

31. According to Einstein's special theory of relativity,
(a) all properties of matter and energy can be explained in a single mathematical formula.
(b) light is composed of separate packets of energy.
(c) time and motion are relative to the observer.
(d) some solids emit electrons when struck by light.

32. In the sentence, “Einstein spoke out frequently against nationalism, the exalting of one nation above all others”, the word "exalting" most nearly means
(A) elevation
(B) criticism
(C) support
(D) elimination

Vocabulary

33. v. hoax

(a) to dupe; to play a trick on; to deceive
(b) to dirty; to stain; to sully; to soil
(c) to scrape or shave off; to obliterate; to tear down completely; to demolish
(d) to avoid; to outwit; to get around

34. v. extirpate

(a) to attract; to tempt; to charm
(b) to draw out; to extract from
(c) to refer indirectly to something; to hint
(d) to root out; to destroy totally; to eradicate

35. v. flaunt

(a) to smile in a silly or affected way; to smirk
(b) to foil; to thwart; to disappoint; to defeat; to baffle
(c) to display or wave boastfully
(d) to start; to provoke; to inflame; to incite

36. v. ensue

(a) to start; to provoke; to inflame; to incite
(b) to follow; to result
(c) to speak angrily or bitterly; to protest forcefully; to rant
(d) to cancel by authority; to terminate; to abolish

37. v. concede

(a) to guess; to speculate; to surmise; to hypothesize; to infer
(b) to postpone; to put off to another time; to delay; to hold back
(c) to surrender; to admit; to give up; to yield
(d) to accuse falsely or maliciously in order to injure another's reputation; to slander

38. adj. sleazy

(a) carefully attentive; diligent; persistent; hard-working
(b) mutual; having the same relationship to each other; common; joint
(c) flimsy and cheap; shabby; cheap
(d) separate; individual

39. v. fathom

(a) to give up; to put off until later
(b) to approve; to support; to tolerate; to permit
(c) to understand; to get to the bottom of; to measure the depth of
(d) to imprison; to detain; to jail

40. v. consecrate

(a) to dupe; to play a trick on; to deceive
(b) to variegate; to make different; to increase the product range of a company; to offer new products
(c) to declare sacred; to dedicate; to bless
(d) to restate in a brief; concise form; to sum up; conclude; to summarize

41. v. deprecate

(a) to speak or write at great length; to describe in full

(b) to express disapproval of; to protest against; to disparage; belittle
(c) to speak out against; to condemn; to accuse; to censure
(d) to forecast; to foretell; to diagnose

42. n. pedant

(a) person who denies that God exists
(b) stick; staff; wand
(c) meticulous person; fastidious person; strict person; fussy person
(d) increase; profit; growth; addition

43. n. predilection

(a) thoughtlessness; state of complete forgetfulness
(b) favorable opinion arrived at beforehand; affinity; liking; fondness
(c) trickery; deception; scheming
(d) very thin gauzelike fabric or structure; cobweb

44. n. pseudonym

(a) act of erecting (a building); meaning
(b) fictitious name; pen name
(c) harsh rebuke; abusive condemnation; denunciation
(d) incoherent speech; specialized vocabulary in certain fields

45. n. sagacity

(a) nautical unit of depth; unit of length equal to six feet
(b) shrewdness; cleverness; wisdom
(c) historical records; archives; chronicles
(d) flattering speech or act; persuasion

46. n. impostor

(a) affected or silly smile; smirk
(b) meaning; significance; bringing in of goods from another country
(c) person who pretends to be someone else in order to deceive others; pretender; impersonator
(d) historical records; archives; chronicles

47. n. demeanor

(a) point directly overhead in the sky; highest point; climax
(b) hardship; suffering; misfortune; crisis
(c) body (natural or artificial) which revolves around a larger body; generally a planet
(d) behavior; bearing; conduct; appearance

48. n. prelude

(a) place offering shelter and retreat; refuge
(b) disorderly quarrel; tumult; riot; skirmish
(c) introduction; forerunner
(d) conclusion reached by reasoning from data or premises; speculation

Curriculum Vitae

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Education:

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:

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

2013: Ontario Graduate Scholarship - Declined

2013: PSAC Local 610 Academic Achievement Scholarship

2012: Ontario Graduate Scholarship

2006: Dalhousie Entrance Scholarship

Professional Experience:

2011-2013: Teaching Assistant
University of Western Ontario

2011: Technical consultant
Laurentian University

2010: Teaching Assistant
Dalhousie University

2009-2011: Research Assistant
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Publications:

Newman, A.J., Tremblay, A., Nichols, E.S., Neville, H.J., and 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.

Talks:

Peer-Reviewed:

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. May, 2010; 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:

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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.