The role of the left inferior parietal lobule in second language learning: an intensive language training fMRI study

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ABSTRACT

Research to date suggests that second language acquisition results in functional and structural changes in the bilingual brain, however, in what way and how quickly these changes occur remains unclear. To address these questions, we studied fourteen English-speaking monolingual adults enrolled in a twelve-week intensive French language-training program in Montreal. Using functional MRI, we investigated the neural changes associated with new language acquisition. The participants were scanned before the start of the immersion program and at the end of the 12 weeks. The fMRI scan aimed to investigate the brain regions recruited in a sentence reading task both in English, their first language (L1), and in French, their second language (L2). For the L1, fMRI patterns did not change from Time 1 to Time 2, while for the L2, the brain response changed between Time 1 and Time 2 in language-related areas. Of note, for the L2, there was higher activation at Time 2 compared to Time 1 in the left inferior parietal lobule (IPL) including the supramarginal gyrus. At Time 2 this higher activation in the IPL correlated with faster L2 reading speed. Moreover, higher activation in the left IPL at Time 1 predicted improvement in L2 reading speed from Time 1 to Time 2. Our results suggest that learning-induced plasticity occurred as early as 12 weeks into immersive second-language training, and that the IPL appears to play a special role in language learning.

Keywords: second language acquisition; fMRI; inferior parietal lobule; sentence reading

1. INTRODUCTION

It has long been debated how bilingualism may affect the brain networks involved in language processing. The ability to proficiently learn a second language (L2) varies from one individual to another and depends greatly on the age at which it is acquired. Behaviorally, early learners outperform late learners in L2 acquisition (Thomas & Johnson, 2008; Vanhove, 2013), which suggests that learning is acquired most efficiently earlier in life during “optimal” or "critical periods" (Hakuta, Bialystok, & Wiley, 2003; Lenneberg, 1967; Penfield & Roberts, 1959; Werker & Tees, 2005). Although the ability to learn a second language is possible throughout the lifespan (Hakuta, et al., 2003; Marcotte & Ansaldo, 2014; Vanhove, 2013), research shows that the ability to learn a new language may be affected by, among other things, cognitive aging affecting working memory, processing speed and attention (Hakuta, et al., 2003), and the neural changes associated with adult language learning remain poorly understood.

To date there are only a few studies investigating brain plasticity over time specifically related to L2 learning in adulthood. The majority have focused on structural investigations to examine the effect of becoming proficient in a new language. In a Voxel-based Morphometry (VBM) study, Stein et al. (2012) observed structural changes in the left inferior frontal gyrus (IFG) after five months of L2 immersion, a change that was related to the acquired proficiency in that L2. Similarly, Mårtensson et al. (2012) observed structural differences after three months of language learning, in bilateral hippocampus, the left middle frontal, IFG and superior temporal gyrus (STG) for second language learners compared to controls. Xiang et al. (2015) observed structural changes in temporoparietal white matter after only six weeks of learning a new language. Schlegel, Rudelson, and Tse (2012) studied the white matter changes after nine months of intensive Chinese learning and observed structural changes directly associated with the degree language learning in classical left hemisphere language areas. Among the studies that have looked at the effect of language learning using functional neuroimaging, Golestani and Zatorre (2004) showed that after only two weeks of Hindi phonetic learning, changes occurred in the fMRI signal in classical frontal operculum and parieto-temporal speech regions in relation to behavioral improvement. Wong and colleagues (2007) found changes in a network of cortical regions including the IFG, prefrontal, medial frontal, medial temporal, posterior parietal and inferior temporal areas in English-speaking subjects trained to identify pitch patterns; the posterior STG was specifically related to successful learning. A study using magnetoencephalography (MEG) observed a learning effect mainly in the inferior parietal lobe (IPL) after training on a new word learning task (Cornelissen, et al., 2004). Mestres-Missé (2009) also observed increased activation in the IPL (as well as in the left IFG, middle and STG, anterior cingulate and some subcortical structures) associated with the on-line process of new-word learning. These previous studies suggest that the brain circuitry including the left IFG, IPL and STG supports language learning in adulthood.

The role of the IPL in L2 learning is becoming increasingly evident. Della Rosa, et al. (2013) in fact have described the IPL as the "location for multilingual talent" given that these authors observed greater gray matter density in the IPL in bilinguals that positively correlated with a behavioral measure of multilingual competence. One of the first empirical observations for a special role of the IPL in second language learning comes from a study by Mechelli and colleagues (2004) which found that grey matter density increases in the left IPL were associated with higher L2 proficiency in bilinguals. Grogan, et al. (2012), related grey matter density increases in the IPL (posterior supramarginal gyrus) in multilingual participants to the number of words learnt. Lee and colleagues (2007) have also found a relationship between grey matter density in the left supramarginal gyrus (part of the IPL), and vocabulary learning. White matter density in an adjacent IPL region has also been related to speech sound production performance (Golestani & Pallier, 2007).

In the present study, we aimed to shed additional light on brain changes associated with learning a new language in adulthood. In contrast to the studies thus far reported in the literature (Cornelissen, et al., 2004; Golestani & Zatorre, 2004; Mestres-Misse, et al., 2009; Wong, et al., 2007) which focus on specific types of language training in a laboratory setting, we sought to explore neural changes after immersive naturalistic language training. We also sought to examine the relationship between functional brain activations and L2 learning outcome. To do so, we studied English (L1) monolingual adults enrolled in an intensive French (L2) immersion program, using fMRI and a sentence reading task. Participants were scanned before and after the intensive training program on an overt sentence-reading task, which was used to capture most of the language processes that would be involved in reading, including processing the sentences and producing speech. Proficiency levels of the participants were assessed pre- and post-training.

2. MATERIALS AND METHODS

2.1. Participants

Fourteen right-handed English-speaking monolingual adults were enrolled in a 12-week intensive French immersion language-training program in Montreal (see Table 1). Intelligence was assessed using the Block Design subtest of the Wechsler Abbreviated Scale of Intelligence (WASI). Participants were screened through a questionnaire to exclude individuals with neurological, psychiatric, or medical conditions. Participants were excluded if they had knowledge of another language other than English, if they had a high degree of musical skill, uncorrected visual impairment, or any hearing or reading impairment. Participants were students from outside of Quebec (9 from other provinces of Canada, 2 from the USA, 3 from UK) who had some exposure to French since arriving in Quebec, but considered themselves at the time of initial assessment as solely speakers of English. All of them attended English schools and went to English Universities. Written informed consent was obtained from all participants in accordance with the Research Ethics Board of the Montreal Neurological Institute .

-TABLE 1 HERE-

2.2. French training course

Participants completed an intensive French (L2) training course for 6 hours per day, 5 days a week for twelve weeks, as part of “The Certificate of Proficiency in French – Language and Culture” program offered by the School of Continuing Studies at McGill University. The course developed competencies in complex communicative exchanges and reading and used a real-world immersive type of design focused on conversations and learning from context (combination of classroom instruction in French, conversation partners, and frequent cultural activities and interaction with native speakers). Such a naturalistic approach, with increased target exposure to L2 throughout the day is thought to lead to better second language learning outcomes, compared to more classical textbook classroom teaching (Dahl & Vulchanova, 2014), which in turn can optimise learning in this short period of time (12 weeks) and contribute to better proficiency in reading and vocabulary, as measured in the current study.

2.3. Protocol

All participants were tested at Time 1, before the intensive French learning program and at Time 2, at the end of the twelve weeks. Testing at each time-point included behavioral tasks, both in the L1 and L2, as well as a MRI session.

2.3.1. Behavioral measures

The behavioral testing session outside of the scanner consisted of both qualitative and quantitative language assessment measures. Qualitative information was obtained from the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007), with self-reported ratings of language competence in reading, speaking and comprehension of the L1 and L2. For the quantitative assessment participants read standardized paragraphs aloud in L1 and L2, and produced 2-minute spontaneous speech samples in the L1 and L2 by describing scenarios using relevant vocabulary, such as describing their typical day at the beach or zoo. The reading samples and speech samples were digitally recorded. For paragraph reading, reading speed, calculated as words per minute (as per the method of Dehaene, et al., 2010), was used as a proficiency measure at Time 1 and Time 2. For the spontaneous speech sample, we calculated a vocabulary measure, by counting the number of novel and correctly used words.

2.3.2. Task and Stimuli

fMRI scans were obtained while participants read aloud short written sentences presented on the screen in the L1 and L2. The conditions (L1 reading, L2 reading, baseline) were presented in a pseudo-random predetermined order as blocks of 3-6 sentences of the same condition. The sentences were presented as black text on a white background for 7.5 seconds. Participants were asked to read the sentence aloud during the 7.5 second silent interval (no scanner noise) provided by the sparse sampling design (Gracco, Tremblay, & Pike, 2005), followed by a 2.5 second whole brain acquisition. To capture the brain activation related to all aspects of sentence reading, and speech production, we compared sentence reading to a low-level baseline control condition, where participants visually scanned the string of X's, following the structure of the sentences, as if reading the X's silently. A representative baseline sentence included: *Xxxxx xxxxxxxx xxxx xx xxx xxxx*. A total of 48 English, 48 French, and 24 control sentences were presented to each participant.

The English (L1) and French (L2) sentences included an article, noun, verb [preposition if necessary], article, and noun. Representative phrases for English included: *An airplane flew over the village*, *The parrot bites his cookie*. Representative phrases for French included: *Le mari dansait avec sa femme*, *Ce garçon achète des souliers*. English nouns and verbs were selected from the medium and high frequency lists (Masterson & Druks, 1998) of the CELEX lexical database (Baayen, Pipenbrock, & van Rijn, 1995) and were translated to French equivalents, but from the total lists created, each participant saw different stimuli in English and in French. Phrases were in the present or imperfect tense and were controlled for the number of syllables (English, average 7.8 range 6–10;, French, average 8.0, range 6–10; [p = .095, ns]). English and French are languages with moderate orthographic depth, in that their spelling-sound correspondences are not highly consistent (Goswami, 2008; Ziegler & Goswami, 2005). Sentences were, therefore, constructed to minimize such irregularities and all followed the same format. A high quality optical microphone (Sennheiser MO 2000) recorded overt reading responses.

2.3.3. MRI data acquisition

Images were acquired on a Siemens 3T Magnetom Trio A Tim System with a 32-channel head coil at the McConnell Brain Imaging Center of the Montreal Neurological Institute (McGill University). The scanning session included an anatomical T1-weighted structural brain image obtained with a gradient-echo MP-RAGE sequence (176 slices, interleaved, 1 mm^3 voxels, TR = 2300 ms, TE = 2.98 ms, flip angle = 30°, slice thickness = 1mm, matrix size = 256 x 256, FOV = 256 mm). Functional data were acquired using a sparse-sampling design and an EPI sequence (TR = 10 000 ms, 42 oblique slices, 3.5 mm^3 voxels, slice thickness = 3.5 mm, TE = 30 ms, flip angle = 90°).

2.4. fMRI image analysis

2.4.1. Preprocessing

SPM8 was used for preprocessing and statistical modeling. During preprocessing, images were corrected for slice timing using the middle slice as reference and were realigned using a 6 parameters procedure (involving the 3 translations and 3 rotations) and unwarped using at two-pass procedure and a 5 mm full-width-at-half-maximum (FWHM) Gaussian filter. Scans for each participant were then coregistered to the T1 anatomical scan that were acquired in the same scanning session, segmented into gray matter, white matter and CSF, spatially normalised into the ICBM152 MNI space and smoothed with a 3-D Gaussian filtering kernel of 8 mm FWHM.

2.4.2. Statistical modeling

First-level analyses for each subject were conducted with a design matrix including each of the three conditions (English, French, X-baseline). The whole 7.5 second duration given to read the sentences was used in the model in order to capture the most complete language processing mechanisms related to reading, processing and producing the sentences. A high-pass temporal filter with a cutoff of 128 seconds was used to remove low-frequency noise. The hemodynamic response was modeled with the canonical hemodynamic function implemented as boxcar basis functions in SPM8. Contrasts were computed for English vs. baseline and French vs. baseline. Second-level analyses were then conducted by entering the first level contrasts of each subject at Time 1 and Time

2 in a paired-sample *t*-test in order to investigate changes in task-related brain activation between Time 1 and Time 2. A critical threshold of *p* uncorrected < .005 and cluster-level FDR-corrected *p* < .05 was used. An additional analysis was performed to compare brain changes from Time 1 to Time 2 in the L2 where learning improved, to brain changes from Time 1 to Time 2 in the L1, where participants did not show any behavioral changes between the two time points. A post-hoc analysis was thus performed to ensure that the brain activation changes were specific to the learning of the L2 and not to time change more globally. To this end we ran an ANOVA on the brain activation in the region that showed the Time 1-Time 2 brain change for learning the L2, with time (Time 1, Time 2) and language (L1, L2) as within-subject factors. The L1 and L2 were not directly compared to each other since L2 proficiency was low before training and remained lower than the L1 after training, and it is thus difficult to determine the extent to which the brain regions activated might be affected by proficiency levels when comparing a highly proficient L1 and a low proficiency L2 (Meschyan & Hernandez, 2006).

2.4.3. Regression analyses

For the L2 we ran two regression analyses to relate brain activations to behavior. To test whether pre-training brain activations predicted reading improvement across individuals, brain activation at Time 1 was related to improvement in paragraph reading speed from Time 1 to Time 2. To understand in what way post-learning brain activations were related to outcome reading performance, brain activation at Time 2 was then related to reading performance on the paragraph reading speed measure after learning. In addition, to ensure that the activity observed was indeed related to learning and not to reading speed in general, brain activation for the L1 was related to L1 reading speed (participants were highly proficient in their L1 but varied in their natural reading speed). Critical thresholds of *p* uncorrected < .005, and cluster-level FDR-corrected *p* < .05 were used.

3. RESULTS

3.1. Behavioral measures

On the LEAP-Q self-rating questionnaire, participants ratings of their language ability did not differ from Time 1 to Time 2 for their L1 ($p>.30$), but they reported significantly increased ability from Time 1 to Time 2 for the L2 for all three measures, for Reading ($p=.001$), Speaking ($p<.001$) and Comprehension ($p=.03$).

On the paragraph reading task that was performed outside of the scanner, reading speed (words per minute) improved between Time 1 and Time 2 (*t*-test: $t(13)=-6.469$, $p<.001$) in L2. Not unexpectedly, for the L1 reading speed did not differ significantly at Time 1 and Time 2 ($p=.08$). For the spontaneous speech sample, compared to Time 1, participants showed significant improvement at Time 2 in the L2 for the number of novel words correctly produced, ($t(14) = 8.3$, $p < .001$), an index of increased vocabulary attainment. Again, there was no difference between Time 1 and Time 2 in the L1 on vocabulary usage ($p=.53$). Of interest, for the L2 the paragraph reading speed and the vocabulary measure from the spontaneous speech sample were correlated at Time 2 ($r=.551$, $p=.041$) and the correlation approached significance at Time 1 ($r=.479$, $p=.083$).

In-scanner sentence reading duration (seconds) in L2 significantly improved from Time 1 to Time 2 (*t*-test: $t(13)=2.443$, $p=.030$) but did not differ significantly from Time 1 to Time 2 (*t*-test: $t(13)=.493$, $p=.630$) in the L1. In-scanner reading speed was positively correlated with paragraph reading speed (L2: Time 1, $r=-.962$, $p<.001$; Time 2, $r=-.617$, $p=.019$; L1: Time 1, $r=-.639$, $p=.014$, Time 2, $r=-.530$, $p=.051$). See Table 2 for all behavioral results.

-TABLE 2 HERE-

3.2. L1 task-related brain activation at Time 1 and Time 2

As expected from L1 sentence reading tasks, overt sentence reading in the scanner at both Time 1 and Time 2, activated several classic language processing areas bilaterally (left greater than right), including the inferior frontal and superior temporal regions, the insula, the precentral region and the cerebellum, as well as the left inferior parietal region (see Table 3). No significant differences were observed between Time 1 and Time 2 for the L1 reading condition. See Figure 1.

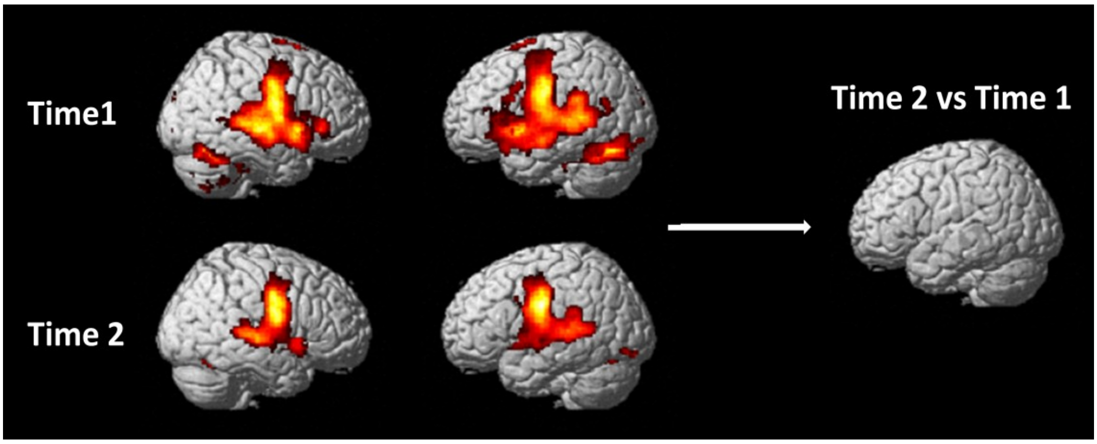

Figure 1. Brain activation related to the sentence reading task in the L1, English, at Time 1 and Time 2. There was no significant difference for the Time 2 vs. Time 1 contrast.

- TABLE 3 HERE -

3.3. L2 task-related brain activation at Time 1 and Time 2

At both Time 1 and Time 2 there was some overlap in recruitment of regions observed for the L1 sentence reading task. However, after intensive language training for the L2, in a direct comparison (Time 2>Time 1), a single cluster of higher activation was observed in the left parietal region, namely the IPL (Figure 2, Table 4). For Time 1>Time 2 higher activation was observed in the right hemisphere in the middle frontal gyrus, caudate, anterior cingulate, insula, inferior precentral gyrus and STG. See Table 4.

-TABLE 4 HERE -

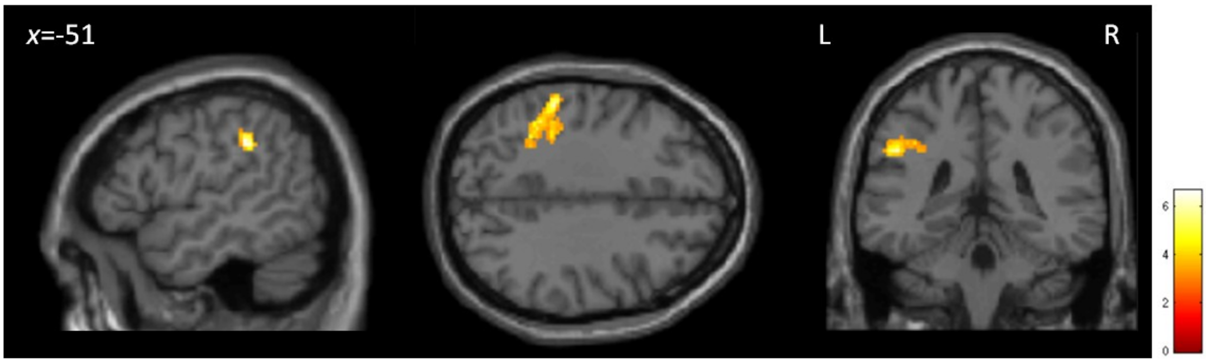

Figure 2. Higher L2 reading task-related activation at Time 2 than Time 1 in the left inferior parietal lobule.

3.4. IPL activations in L1 and L2

In order to ensure that the increase in activation in the IPL observed in the L2 post-training was related to L2 learning, we extracted the average brain activations in the IPL cluster during both L1 and L2 reading, and ran an ANOVA which showed that there were Language (F=31.76, p<.001) and Time (F=6.36, p=.026) effects, as well as a Language X Time interaction (F=6.09, p=.028), the Time 2>Time 1 brain changes being specific to L2 processing.

3.5. Pre-learning brain activation predicting improvement in L2 reading performance from Time 1 to Time 2

To investigate whether brain activation before the learning process predicts reading improvement in L2, a whole-brain regression analysis was run to investigate the relationship between the Time 1 sentence reading brain activation and L2 improvement (Time 2 minus Time 1) using the measure of paragraph reading speed. One cluster of activation encompassing part of the left inferior parietal lobule (IPL; angular gyrus, BA 40/39) and the superior temporal gyrus (Figure 3, Table 5), was observed to be significantly related to improvement in paragraph reading speed from Time 1 to Time 2.

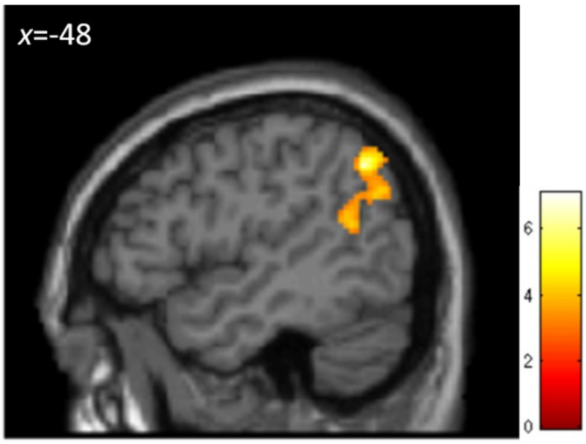

Figure 3. Brain activation in the left IPL at Time 1 related to improvement in paragraph reading speed from Time 1 to Time 2.

- TABLE 5 HERE -

3.6. Relationship between post-learning brain activation and L2 performance

A second regression analysis was run to investigate the relationship of the post-learning brain activation and L2 performance after-learning, as measured by the reading speed calculated from the out-of-scanner paragraph reading sample. This whole-brain analysis showed that higher brain activation (at Time 2) in the left IPL was related to faster Time 2 reading speed (Figure 4, Table 6). To ensure the observed effects were indeed directly attributable to L2 learning, and not due to other cognitive changes associated with the training experience, we used the L1 as an internal control. For the L1 there were no brain regions that showed a relationship between activation levels and L1 reading speed, suggesting that the IPL does not simply track the natural variation of reading speed. We ran further correlation analyses between the brain activation extracted from the IPL clusters and our other quantitative behavioral L2 proficiency measure, the vocabulary measure obtained from the spontaneous speech sample. Both at Time 1 and Time 2, the brain activation in the IPL did not correlate with the vocabulary measure. However, the amount of difference in brain activation between Time 1 and Time 2 in the IPL region that predicted improvement in reading speed was correlated with French vocabulary improvement from Time 1 to Time 2 (*r*=.562, *p*=.036).

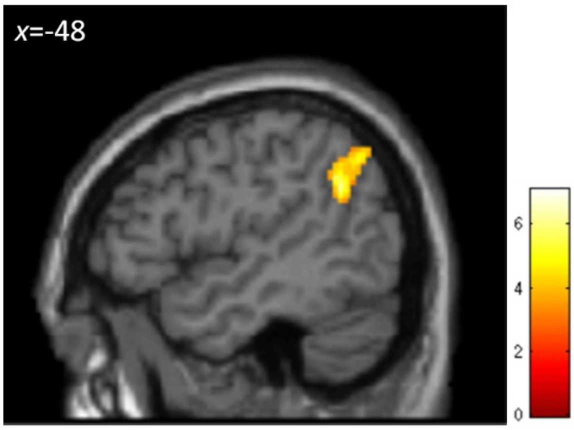

Figure 4. Brain activation in the left IPL at Time 2 related to faster paragraph reading at Time 2.

- TABLE 6 HERE -

3.7. Visual comparison of current and previous findings

In a final step we sought to examine how our results compared to other studies showing a relationship between the IPL and language learning. We projected our three results for the L2 (Time 2 vs Time 1, Time 1 regression, and Time 2 regression) onto a 3D brain and superimposed the coordinates of five different studies from the literature (Golestani & Pallier, 2007; Golestani & Zatorre, 2004; Lee, et al., 2007; Mechelli, et al., 2004; Mestres-Misse, et al., 2009). As can be seen in Figure 5, our functional findings (green, red and blue clusters) overlap with evidence from these studies using structural and functional brain imaging, suggesting that parallels can potentially be made between the structural differences that are observed in the IPL in relation with L2 acquisition and the differences in functional brain processing we observed after learning an L2.

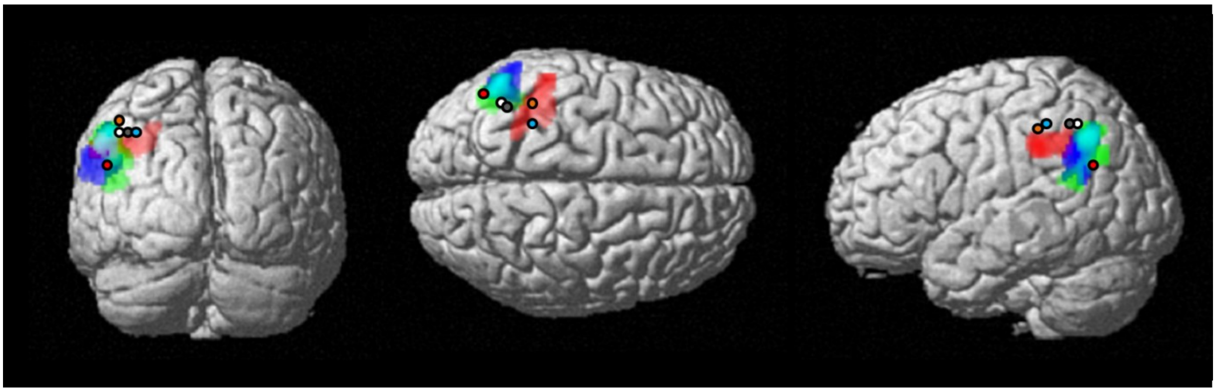

Figure 5. Overlap between the Mechelli et al. (2004) coordinate [-45, -59, 48] (black and white circle), the Golestani and Zatorre (2004) coordinate [-54, -66, 26] (black and red circle), the Lee et al. (2007) coordinate [-44, -54, 46] (black and grey circle), the Golestani and Pallier (2007) coordinate [-34, -41, 46] (black and light blue circle), the Mestres-Missé et al. (2009) coordinate [-44, -40, 52] (black and orange circle) and the activation cluster from the Time 2 > Time 1 second level analysis (RED), the cluster from Time 1 fMRI activation related to reading speed improvement (GREEN) and the cluster from Time 2 fMRI activation related to reading speed (BLUE).

4. DISCUSSION

In our study, neural changes were observed during the process of learning an L2 during adulthood. First, a whole brain analysis revealed that the left IPL was more activated at Time 2 than at Time 1. Additional separate analyses consistently showed that brain activation in this IPL region was associated with behavioral measures of L2 success. Greater brain activation at Time 1 in the left IPL was related to L2 improvement in paragraph reading speed. In addition, higher activation in the IPL at Time 2 was related to faster reading in the L2 at Time 2.

The left IPL, of which the supramarginal gyrus is part, has long been implicated as playing an important role in language processing (e.g.: Price, 1998 for a review). The IPL's role has been related to phonological working memory, semantics and lexical learning (Cornelissen, et al., 2004; Li, Legault, & Litcofsky, 2014). Using independent component analysis (ICA) analysis, Geranmayeh, et al. (2012) have also pointed out a role for the left IPL in a distributed cortical network important for formulating and producing of spoken sentences. The IPL has also been specifically implicated, as part of a network with frontal areas, in word learning (Lopez-Barroso, et al., 2013; Lopez-Barroso, et al., 2015; Mestres-Misse, et al., 2009), through the process of mapping sounds onto motor speech representations involved while acquiring new vocabulary (Rodriguez-Fornells, Cunillera, Mestres-Misse, & de Diego-Balaguer, 2009). In addition, it has been suggested that a more posterior area of the parietal lobe, the somatosensory association cortex (BA 7), plays a role in articulation processes requiring sensory monitoring that is needed to a greater extent when processing an L2 than an L1 (Simmonds, Wise, Dhanjal, & Leech, 2011).

Our results support the notion of a special role for the left IPL related to language learning (Della Rosa, et al., 2013). Although in our study we did not have a control group to assess changes with a different training task (i.e. non-language training, see Melby-Lervag & Hulme, 2013; Shipstead, Redick, & Engle, 2012), nor a control for assessing brain changes with no training over twelve weeks, it remains likely that the functional brain changes we observed are indeed related specifically to the learning of the L2, since we were able to assess changes in brain activation over 12 weeks for the proficient “non-changing” language, the L1. If factors unrelated to learning were causing the increased IPL activations during L2 reading from Time 1 to Time 2, we would have expected to see the same increase in L1. In our study, the difference between Time 1 and Time 2 appeared to be specific to L2 processing, as there were no task-related changes from Time 1 to Time 2 for the L1. Moreover, our results add support and are consistent with other language learning functional imaging studies; in one that focussed on phonetic learning, activation in the IPL was also modulated by language improvement (Golestani & Zatorre, 2004), and in an fMRI study that used an online new-word learning task (Mestres-Misse, et al., 2009) the IPL was also shown to be implicated. We observed a correlation between the increased activation in the IPL and increase in vocabulary size. These results suggest that the increased IPL activation after training may be related to the increased lexical knowledge and usage which led to increased comprehension of the L2 after learning. Dahl and Vulchanova (2014) showed an increase in receptive vocabulary in a "naturalistic L2 learning" group compared to a "classical classroom L2 learning" group of children. Similar to Dahl we relate our results to increased L2 vocabulary and comprehension as a consequence of learning. Given that there was no relationship between IPL activation and reading speed in the L1 add support that the IPL activation does not simply reflect natural variations in reading speed. It is of note that the cluster of brain activation at Time 1 that was related to reading improvement extends posteriorly in the IPL to include the angular gyrus. The angular gyrus has been shown to be active in a narrative context compared to a simple sentence condition with less coherence in meaning (Xu, Kemeny, Park, Frattali, & Braun, 2005) and activation in the angular gyrus during a semantic processing sentence reading task has been associated with language abilities (Van Ettinger-Veenstra, McAllister, Lundberg, Karlsson, & Engstrom, 2016). Activation in BA 7 after the L2 training additionally supports the idea of greater effort involved in monitoring articulation while reading the sentences, likely related to increased understanding of what is being read and increased knowledge as to how the words should be pronounced. The link between reading speed and increased comprehension remains to be tested directly, given that in our study we did not have a higher level baseline condition (e.g. pseudoword sentences), thus making it difficult to verify the contribution of comprehension/semantics in our study.

Given that our participants remained at a low level of proficiency, even at Time 2, our study was also not able to address whether the IPL is transiently implicated during the learning process or whether changes in the IPL are associated with a stable state once an individual has become more proficient in the L2. However, the literature on bilingualism suggests that the IPL changes are not simply a part of a transient phase of the learning process. The IPL has been shown to be related to L2 proficiency even in individuals who have been bilingual for a length of time (more than five years, Mechelli, et al., 2004). Greater grey matter density in the IPL of bilinguals has been related to better language competence (Della Rosa, et al., 2013), better second-language proficiency (Mechelli, et al., 2004), and higher vocabulary learning (Grogan, et al., 2012). This increased IPL grey matter volume has also been replicated in a study where elderly bilinguals were compared to age-matched monolinguals (Abutalebi, Canini, Della Rosa, Green, & Weekes, 2015). In the present study, the fact that the IPL was associated with learning success, not only after, but even before the 12 weeks of immersion, suggests that the properties of the IPL might predict or indicate an advantage for successful language learning, rather than solely represent the consequences of acquiring a second language.

Future research on developmental language impairments might help refine the role of the parietal lobe and its subregions in language learning and whether, and how, it differs in learning second languages and first language development. Buchweitz (2016) suggested that together with the visual word form area, temporoparietal areas, including the IPL, develop with reading skills development, more specifically, with phonological letter-sound matching abilities, and that these brain regions are hypoactive in individuals with dyslexia (Buchweitz, 2016). Underactivation in the IPL has been reported in a meta-analysis of the functional abnormalities of the dyslexic brain (Richlan, Kronbichler, & Wimmer, 2009). Klingberg and colleagues (2000) studied dyslexic adults with poor reading abilities and observed that they had white mater deficits in bilateral temporoparietal areas. Moreover, the properties of that left temporoparietal white matter were correlated with reading abilities in those poor readers but in normal readers as well. Grey matter reductions in temporoparietal areas is also one of the main structural correlate of dyslexia and are related to reading proficiency (Linkersdorfer, et al., 2015). The structural properties of the parietal cortex also appear to play an important role in delays in language development seen in autism (Zoccante, et al., 2010).

In conclusion, our results confirm an emerging body of literature that suggests a key role for the inferior parietal lobule in the successful acquisition of a second language, specifically when assessing changes in brain function related to sentence reading. We show that changes in language processing in the IPL can be observed as early as 12-weeks during second language learning, and that properties of the IPL, even prior to training, predict better second language learning success.

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REFERENCES

Abutalebi, J., Canini, M., Della Rosa, P. A., Green, D. W., & Weekes, B. S. (2015). The neuroprotective effects of bilingualism upon the inferior parietal lobule: A Structural Neuroimaging Study in Aging Chinese Bilinguals. *Journal of Neurolinguistics, 33*, 3-13.

Baayen, R. H., Pipenbrock, R., & van Rijn, H. (1995). The CELEX Lexical Database. Release 2 [CD-ROM]. In. Philadelphia: University of Pensylvenia.

Buchweitz, A. (2016). Language and reading development in the brain today: neuromarkers and the case for prediction. *J Pediatr (Rio J), 92*, S8-S13.

Cornelissen, K., Laine, M., Renvall, K., Saarinen, T., Martin, N., & Salmelin, R. (2004). Learning new names for new objects: cortical effects as measured by magnetoencephalography. *Brain Lang, 89*, 617-622.

Dahl, A., & Vulchanova, M. D. (2014). Naturalistic acquisition in an early language classroom. *Front Psychol, 5*, 329.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Nunes Filho, G., Jobert, A., Dehaene-Lambertz, G., Kolinsky, R., Morais, J., & Cohen, L. (2010). How learning to read changes the cortical networks for vision and language. *Science, 330*, 1359-1364.

Della Rosa, P. A., Videsott, G., Borsa, V. M., Canini, M., Weekes, B. S., Franceschini, R., & Abutalebi, J. (2013). A neural interactive location for multilingual talent. *Cortex, 49*, 605-608.

Geranmayeh, F., Brownsett, S. L., Leech, R., Beckmann, C. F., Woodhead, Z., & Wise, R. J. (2012). The contribution of the inferior parietal cortex to spoken language production. *Brain Lang, 121*, 47-57.

Golestani, N., & Pallier, C. (2007). Anatomical correlates of foreign speech sound production. *Cereb Cortex, 17*, 929-934.

Golestani, N., & Zatorre, R. J. (2004). Learning new sounds of speech: reallocation of neural substrates. *Neuroimage, 21*, 494-506.

Goswami, U. (2008). The development of reading across languages. *Ann N Y Acad Sci, 1145*, 1-12.

Gracco, V. L., Tremblay, P., & Pike, B. (2005). Imaging speech production using fMRI. *Neuroimage, 26*, 294-301.

Grogan, A., Parker Jones, O., Ali, N., Crinion, J., Orabona, S., Mechias, M. L., Ramsden, S., Green, D. W., & Price, C. J. (2012). Structural correlates for lexical efficiency and number of languages in non-native speakers of English. *Neuropsychologia, 50*, 1347-1352.

Hakuta, K., Bialystok, E., & Wiley, E. (2003). Critical evidence: a test of the critical-period hypothesis for second-language acquisition. *Psychol Sci, 14*, 31-38.

Klingberg, T., Hedehus, M., Temple, E., Salz, T., Gabrieli, J. D., Moseley, M. E., & Poldrack, R. A. (2000). Microstructure of temporo-parietal white matter as a basis for reading ability: evidence from diffusion tensor magnetic resonance imaging. *Neuron, 25*, 493-500.

Lee, H., Devlin, J. T., Shakeshaft, C., Stewart, L. H., Brennan, A., Glensman, J., Pitcher, K., Crinion, J., Mechelli, A., Frackowiak, R. S., Green, D. W., & Price, C. J. (2007). Anatomical traces of vocabulary acquisition in the adolescent brain. *J Neurosci, 27*, 1184-1189.

Lenneberg, E. H. (1967). *Biological foundations of language*. New-York: Wiley.

Li, P., Legault, J., & Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: anatomical changes in the human brain. *Cortex, 58*, 301-324.

Linkersdorfer, J., Jurcoane, A., Lindberg, S., Kaiser, J., Hasselhorn, M., Fiebach, C. J., & Lonnemann, J. (2015). The association between gray matter volume and reading proficiency: a longitudinal study of beginning readers. *J Cogn Neurosci, 27*, 308-318.

Lopez-Barroso, D., Catani, M., Ripolles, P., Dell'Acqua, F., Rodriguez-Fornells, A., & de Diego-Balaguer, R. (2013). Word learning is mediated by the left arcuate fasciculus. *Proc Natl Acad Sci U S A, 110*, 13168-13173.

Lopez-Barroso, D., Ripolles, P., Marco-Pallares, J., Mohammadi, B., Munte, T. F., Bachoud-Levi, A. C., Rodriguez-Fornells, A., & de Diego-Balaguer, R. (2015). Multiple brain networks underpinning word learning from fluent speech revealed by independent component analysis. *Neuroimage, 110*, 182-193.

Marcotte, K., & Ansaldo, A. I. (2014). Age-related behavioural and neurofunctional patterns of second language word learning: different ways of being successful. *Brain Lang, 135*, 9-19.

Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): assessing language profiles in bilinguals and multilinguals. *J Speech Lang Hear Res, 50*, 940-967.

Martensson, J., Eriksson, J., Bodammer, N. C., Lindgren, M., Johansson, M., Nyberg, L., & Lovden, M. (2012). Growth of language-related brain areas after foreign language learning. *Neuroimage, 63*, 240-244.

Masterson, J., & Druks, J. (1998). Description of a set of 164 nouns and 102 verbs matched for printed word frequency, familiarity and age-of-acquisition. *Journal of Neurolinguistics, 11*, 331-354.

Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., & Price, C. J. (2004). Neurolinguistics: structural plasticity in the bilingual brain. *Nature, 431*, 757.

Melby-Lervag, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Dev Psychol, 49*, 270-291.

Meschyan, G., & Hernandez, A. E. (2006). Impact of language proficiency and orthographic transparency on bilingual word reading: an fMRI investigation. *Neuroimage, 29*, 1135-1140.

Mestres-Misse, A., Munte, T. F., & Rodriguez-Fornells, A. (2009). Functional neuroanatomy of contextual acquisition of concrete and abstract words. *J Cogn Neurosci, 21*, 2154-2171.

Penfield, W., & Roberts, L. (1959). *Speech and brain mechanisms*. Princeton: Princeton University Press.

Price, C. J. (1998). The functional anatomy of word comprehension and production. *Trends Cogn Sci, 2*, 281-288.

Richlan, F., Kronbichler, M., & Wimmer, H. (2009). Functional abnormalities in the dyslexic brain: a quantitative meta-analysis of neuroimaging studies. *Hum Brain Mapp, 30*, 3299-3308.

Rodriguez-Fornells, A., Cunillera, T., Mestres-Misse, A., & de Diego-Balaguer, R. (2009). Neurophysiological mechanisms involved in language learning in adults. *Philos Trans R Soc Lond B Biol Sci, 364*, 3711-3735.

Schlegel, A. A., Rudelson, J. J., & Tse, P. U. (2012). White matter structure changes as adults learn a second language. *J Cogn Neurosci, 24*, 1664-1670.

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychol Bull, 138*, 628-654.

Simmonds, A. J., Wise, R. J., Dhanjal, N. S., & Leech, R. (2011). A comparison of sensory-motor activity during speech in first and second languages. *J Neurophysiol, 106*, 470-478.

Stein, M., Federspiel, A., Koenig, T., Wirth, M., Strik, W., Wiest, R., Brandeis, D., & Dierks, T. (2012). Structural plasticity in the language system related to increased second language proficiency. *Cortex, 48*, 458-465.

Thomas, M. S. C., & Johnson, M. H. (2008). New advances in understanding sensitive periods in brain development. *Current Directions in Psychological Science, 17*, 1-5.

Van Ettinger-Veenstra, H., McAllister, A., Lundberg, P., Karlsson, T., & Engstrom, M. (2016). Higher Language Ability is Related to Angular Gyrus Activation Increase During Semantic Processing, Independent of Sentence Incongruency. *Front Hum Neurosci, 10*, 110.

Vanhove, J. (2013). The critical period hypothesis in second language acquisition: a statistical critique and a reanalysis. *PLoS One, 8*, e69172.

Werker, J. F., & Tees, R. C. (2005). Speech perception as a window for understanding plasticity and commitment in language systems of the brain. *Dev Psychobiol, 46*, 233-251.

Wong, P. C., Perrachione, T. K., & Parrish, T. B. (2007). Neural characteristics of successful and less successful speech and word learning in adults. *Hum Brain Mapp, 28*, 995-1006.

Xiang, H., van Leeuwen, T. M., Dediu, D., Roberts, L., Norris, D. G., & Hagoort, P. (2015). L2-Proficiency-Dependent Laterality Shift in Structural Connectivity of Brain Language Pathways. *Brain Connect, 5*, 349-361.

Xu, J., Kemeny, S., Park, G., Frattali, C., & Braun, A. (2005). Language in context: emergent features of word, sentence, and narrative comprehension. *Neuroimage, 25*, 1002-1015.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: a psycholinguistic grain size theory. *Psychol Bull, 131*, 3-29.

Zoccante, L., Viviani, A., Ferro, A., Cerini, R., Cerruti, S., Rambaldelli, G., Bellani, M., Dusi, N., Perlini, C., Boscaini, F., Pozzi Mucelli, R., Tansella, M., Dalla Bernardina, B., & Brambilla, P. (2010). Increased left parietal volumes relate to delayed language development in autism: a structural mri study. *Funct Neurol, 25*, 217-221.

Table 1. Participants characteristics

N	14 (10 F)
Age (*SD*)	24.9 (3.7)
Block Design score (*SD*)	13.2 (2.8)
Formal eduction (years)	16.9 (2.1)

Table 2. Behavioral results at Time 1 and Time 2 for each language.

	French (L2)		English (L1)	
Language assessment	Time 1	Time 2	Time 1	Time 2
Qualitative measures				
LEAP-Q Speaking	1.7 (0.7)	3.1 (0.8) **	9.6 (0.5)	9.6 (0.6)
LEAP-Q Reading	2.7 (1.4)	4.9 (1.8) **	9.6 (0.5)	9.5 (0.8)
LEAP-Q Comprehension	2.6 (1.4)	3.9 (1.6) *	9.5 (0.6)	9.7 (0.5)
Quantitative measures				
Paragraph reading speed (wpm)	78.6 (15.6)	99.8 (15.2) **	174.5 (20.0)	187.9 (20.0)
Spontaneous speech (vocabulary)	11.6 (8.4)	25.4 (7.3) **	61.3 (17.2)	65.2 (15.2)
In-scanner reading duration (sec)	3.04 (0.52)	2.77 (0.47) *	1.80 (0.20)	1.78 (0.23)

* *p*<.05, ** *p*<.001

Table 3. English (L1) reading task-related activations at Time 1 and Time 2 . (MNI coordinates).

		Left					Right				
	BA	x	y	z	*t*	*k*	x	y	z	*t*	*k*
L1 Time 1											
Cerebellum							**20**	**-62**	**-24**	**9.59**	**47738**
		-16	-64	-20	9.35						
		-2	-68	-14	9.04						
Insula/Pre/Post central gyrus	3/4/40/43/44	-48	-14	32	9.58						
	45/47/13						66	-4	14	8.84	
		-64	-10	16	8.36						
							56	-10	20	7.96	
							52	-10	22	7.94	
Superior Temporal gyrus	38	-58	6	-4	9.01						
	41/42/22/21						54	10	-10	8.41	
							62	-20	0	7.99	
		-64	-32	6	7.93						
SMA	6	**-4**	**2**	**74**	**5.78**	**605**					
							8	-6	76	4.12	
							0	10	64	3.65	
L1 Time 2											
Insula/Pre/Post central gyrus	4/6/9	**-48**	**-14**	**32**	**9.64**	**5218**					
	13/40/43/44	-64	-8	16	7.62						
Superior Temporal gyrus	41/42/22/21	-64	-30	6	6.60						
		-58	6	-4	5.98						
		-64	-16	4	5.06						
		-64	-22	4	4.97						
		-64	-42	12	4.60						
		-48	-38	20	4.32						
		-56	-6	-4	4.26						
		-62	-45	8	4.25						
Pre/Post central gyrus	4						**64**	**-2**	**18**	**8.23**	**4478**
							64	-4	14	8.20	
	6						54	-8	34	8.05	
	43/44/38/9						58	-8	20	7.99	
	13/41/42						62	-20	0	6.12	
	21/22						56	-30	4	5.86	
							46	-22	0	4.84	
							68	-38	4	4.44	
							30	0	18	3.61	
							36	-8	16	3.38	
Cerebellum							**20**	**-62**	**-24**	**7.40**	**1804**
		-16	-62	-24	7.35						
		0	-68	-14	5.45						
Cingulate gyrus	30	**-2**	**-68**	**10**	**3.80**	**475**					
							12	-64	8	3.42	
Occipital lobe	18	-16	-56	2	3.20						

Table 4. Difference in brain activation from Time 1 to Time 2 associated to the French sentence reading condition (MNI coordinates).

		Left					Right				
	BA	x	y	z	*t*	*k*	x	y	z	*t*	*k*
Time 2 > Time 1											
Inferior parietal lobule	40	**-54**	**-34**	**36**	**6.64**	**381**					
		-42	-44	40	6.17						
		-34	-48	36	4.68						
Time 1 > Time 2											
Insula/Precentral gyrus/ Superior Temporal gyrus	13,44						**46**	**-6**	**10**	**5.78**	**406**
	22						50	-8	2	4.57	
	6						56	-2	8	4.20	
Middle Frontal gyrus	10						**20**	**38**	**-4**	**5.59**	**681**
							14	30	8	4.14	
							32	26	14	3.95	

Table 5. Brain regions where activation at Time 1 is related to improvement in paragraph reading speed improvement from Time 1 to Time 2.

		Left					Right				
	BA	x	y	z	*t*	*k*	x	y	z	*t*	*k*
Inferior parietal lobule	40/39	**-50**	**-58**	**42**	**7.09**	**395**					
		-44	-66	32	5.21						
		-44	-50	20	5.10						

Table 6. Brain regions where activation at Time 2 is related to faster paragraph reading at Time 2.

		Left					Right				
	BA	x	y	z	*t*	*k*	x	y	z	*t*	*k*
Inferior parietal lobule	40/39	**-52**	**-54**	**36**	**6.78**	**433**					
		-52	-62	42	5.19						
Superior temporal lobe		-64	-48	22	3.21						

Table 7. Brain regions where activation at Time 2 is related to faster in-scanner sentence reading at Time 2.

		Left					Right				
	BA	x	y	z	*t*	*k*	x	y	z	*t*	*k*
Inferior frontal/Insula,	47/38/13	**-32**	**16**	**-18**	**8.61**	**337**					
Superior temporal lobe		-46	20	-12	5.18						
		-28	18	-6	5.01						
Inferior/Middle frontal lobe	45/47/46	**-38**	**32**	**6**	**6.10**	**440**					
		-54	34	2	4.86						
		-46	42	8	4.47						
Inferior parietal lobule	40	**-62**	**-36**	**34**	**5.97**	**492**					
		-54	-36	36	5.28						
		-52	-46	40	5.03						