Cerebral Cortex February 2010;20:315–327
doi:10.1093/cercor/bhp101
Advance Access publication May 28, 2009

# The Impact of Second Language Learning on Semantic and Nonsemantic First Language Reading

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**The relationship between orthography (spelling) and phonology (speech sounds) varies across alphabetic languages. Consequently, learning to read a second alphabetic language, that uses the same letters as the first, increases the phonological associations that can be linked to the same orthographic units. In subjects with English as their first language, previous functional imaging studies have reported increased left ventral prefrontal activation for reading words with spellings that are inconsistent with their orthographic neighbors (e.g., PINT) compared with words that are consistent with their orthographic neighbors (e.g., SHIP). Here, using functional magnetic resonance imaging (fMRI) in 17 Italian–English and 13 English–Italian bilinguals, we demonstrate that left ventral prefrontal activation for first language reading increases with second language vocabulary knowledge. This suggests that learning a second alphabetic language changes the way that words are read in the first alphabetic language. Specifically, first language reading is more reliant on both lexical/semantic and nonlexical processing when new orthographic to phonological mappings are introduced by second language learning. Our observations were in a context that required participants to switch between languages. They motivate future fMRI studies to test whether first language reading is also altered in contexts when the second language is not in use.**

## Introduction

In this paper, we ask how the neural basis of reading in one's native language changes when a second language is learnt. The relevance of this question can be appreciated by considering what happens to Italians when they learn to read in a second language. In Italian, the spelling of a word is remarkably consistent with its sound (Frost et al. 1987; Nyikos 1988; Goswami et al. 2001), therefore, once the spelling-to-sound relationships are learnt, words can be read accurately from their spellings, even if the word has not been read before. When an Italian reader learns a second language with the same Roman alphabet but a different spelling-to-sound relationship, for example English, the same letter combinations are linked to different sounds. The letter combination "CH," for example, is pronounced differently in Italian and English. An Italian–English bilingual reader will therefore be faced with inconsistency in the possible pronunciations for the same letter combination. Such inconsistency in mapping spelling-to sound must be resolved because psycholinguistic data have shown that bilinguals cannot restrict access to the representations of words in other languages (Van Wijnendale and Brysbaert 2002; Brysbaert and Dijkstra 2006; Smits et al. 2006; Thierry and Wu 2007) and this results in interference between the representations for different languages (Rodriguez-Fornells et al. 2002, 2005). Therefore, Italian–English bilinguals must suppress interference from Italian letter–sound correspondences when reading in English and conversely suppress interference from English letter–sound correspondences when reading in Italian. As a consequence, we predict that bilingualism will increase the demands on the process of mapping spelling-to-sound in both languages, particularly when they are required to switch back and forth between languages.

A further consequence of learning to read 2 languages with inconsistent spelling-to-sound relationships is that successful reading in the native language may become more dependent on lexical or semantic processing. This prediction stems from well-established cognitive models of reading in English. Unlike Italian, the spelling-to-sound mapping in English is inconsistent. The letter combination "INT" for example is pronounced differently in the 2 English words "PINT" and "MINT." There are many examples of spelling-to-sound inconsistency in English with 1120 graphemes representing 40 phonemes (Nyikos 1988) as compared with only 33 graphemes representing 25 phonemes in Italian (Lepschy and Lepschy 1981). As a result of spelling-to-sound inconsistency in English, reading requires more lexical or semantic mediation (Paulesu et al. 2000). Put another way, knowledge of a word and its meaning helps to resolve conflicting pronunciations (Plaut et al. 1996). In this paper, we apply the same rationale to reading in 2 languages. Our argument is that, learning to read in a second language, with the same alphabet, adds inconsistency to spelling-to-sound mappings. As a consequence of this inconsistency, successful reading will increase the demands on lexical or semantic processing in both the native and non-native language.

To examine the effect of second language learning on first language reading, we used functional magnetic resonance imaging (fMRI). Lexical/semantic and nonlexical reading areas could then be dissociated on the basis of the pattern of regional brain activation for different types of words in English. There is a long history documenting the processing requirements for reading different types of English words (Coltheart 1981; Seidenberg and McClelland 1989; Paap and Noel 1991; Plaut et al. 1996). All theories assume that, in translating an alphabetic letter string or word into a pronunciation, readers employ both word-specific knowledge and nonlexical knowledge about the way in which combinations of letters typically correspond to phonological representations. The nonlexical knowledge enables pronunciation of words or pseudowords that the reader has never encountered before (e.g., RINT). The lexical/semantic knowledge permits word comprehension and also contributes to achieving the correct pronunciation of "irregular words" (e.g., PINT) that violate statistically typical spelling-to-sound correspondences. Behavioral studies have shown that reading is most efficient for regular words (like MINT) when both lexical/semantic knowledge and nonlexical spelling-to-sound correspondences are consistent (Ziegler et al. 2003), but word frequency and imageability also play a role because when atypically spelled words are highly familiar (e.g., HAVE) or imageable (e.g., KNIFE), they can be read as fast as less familiar but regularly spelled words (Strain et al. 2002; Frost et al. 2005; Katz et al. 2005).

Previous functional neuroimaging studies in normal readers have already investigated how neuronal activation varies with word type (Petersen et al. 1990; Price et al. 1996; Rumsey et al. 1997; Herbster et al. 1997; Fiez et al. 1999; Hagoort et al. 1999; Mechelli et al. 2003, 2005; Paulesu et al. 2000; Tagamets et al. 2000; Xu et al. 2001; Fiebach et al. 2002; Binder et al. 2005; Frost et al. 2005; Katz et al. 2005; Pugh et al. 2008). The most consistent finding is that activation is higher for pseudowords than familiar words in left frontal (Price et al. 1996; Fiebach et al. 2002; Joubert et al. 2004, Heim et al. 2005; Carreiras et al. 2007) and left posterior occipito-temporal regions (see Mechelli et al. 2003 for a review of early studies). However, as noted above, the comparison of pseudowords and familiar words does not control for familiarity, therefore increased activation for pseudowords relative to regularly spelled words may simply be a consequence of pseudowords being less familiar and more difficult (i.e., slower) to read. Indeed, the areas more activated for pseudoword reading overlap with those associated with low versus high frequency word processing (Fiez et al. 1999; Fiebach et al. 2002; Ischebeck et al. 2004; Joubert et al. 2004; Peng et al. 2004). In addition, although successful pseudoword reading depends on nonlexical spelling-to-sound processing, pseudoword reading activation may result, in part, from an unsuccessful lexical/semantic search (see Forster and Bednall 1976; Price et al. 1996) and the need to resolve interference between nonlexical and lexical/semantic processing. Likewise, although low-frequency words with irregular spellings cannot be read successfully using nonlexical spelling-to-sound correspondences, activation differences for reading words with irregular relative to regular spellings may result, in part, from unsuccessful nonlexical processing and the need to resolve interference between nonlexical and lexical/semantic processing. Differences between pseudoword or irregular word reading relative to regular word reading can therefore be difficult to interpret. Nevertheless, by comparing the relative pattern of activation for pseudowords, irregularly spelled words and regular words (Herbster et al. 1997; Fiez et al. 1999; Binder et al. 2005; Frost et al. 2005; Mechelli et al. 2005), it is possible to tease apart effects that are due to processing load per se (i.e., common to pseudowords > regularly spelled words and irregular > regular words) from activation that is greatest for either pseudoword reading or irregular word reading. Moreover, it is also possible to validate these word-type effects by comparing them to the pattern of activation during phonological versus semantic tasks when word type is held constant (see Price and Mechelli 2005). Using this approach, we have previously dissociated 3 different effects of word type (Mechelli et al. 2005):

1) A region in the left premotor cortex is more activated for reading pseudowords than low-frequency words with both regular and irregular spellings;
2) A region in the left ventral inferior frontal cortex is more activated by reading low-frequency irregularly spelled words than pseudowords; and
3) A region in the left pars opercularis is commonly activated by pseudowords and low-frequency irregularly spelled words relative to low-frequency regularly spelled words.

Importantly, the double dissociation in left premotor and left ventral inferior frontal cortex for pseudoword versus irregular word reading is consistent with studies that compare phonological and semantic decisions while keeping word type consistent (Fiez 1997; Roskies et al. 2001; Devlin et al. 2003; McDermott et al. 2003; Price and Mechelli 2005; Booth et al. 2006). It follows that activation in the left premotor cortex is likely to reflect nonlexical phonological processing, whereas activation in the left ventral inferior frontal cortex is likely to reflect lexical/semantic mediation. In addition, on the basis of behavioral studies showing that pseudowords and low-frequency irregular words are read more slowly than low-frequency regularly spelled words (Strain et al. 2002; Ziegler et al. 2003), we can also deduce that activation in the left pars opercularis reflects processing load (e.g., Fiez et al. 1999; Mechelli et al. 2005), possibly due to interference between nonlexical and lexical/semantic processing.

On the basis of these prior studies, we therefore predict that learning to read a second language with the same alphabet will modulate first language activation in: 1) left premotor regions associated with nonlexical reading; 2) left ventral prefrontal areas associated with lexical/semantic reading; and 3) the left pars opercularis associated with processing load when nonlexical and lexical/semantic processing are inconsistent. These findings would provide a novel perspective on bilingualism by highlighting plasticity within the neural system for first language processing and demonstrating that the effect of proficiency on second versus first language processing are not entirely due to changes in second language processing. Such results would also contrast with, but not contradict, the majority of previous fMRI studies of bilingualism (see Perani and Abutalebi 2005 for a review) that have demonstrated 1) a remarkable overlap in the neuronal systems that support different languages even those with very different orthographies (Klein et al. 1999; Chee et al. 2000; Crinion et al. 2006; Yokoyama et al. 2006); 2) increased activation for second relative to first language processing in fronto-cerebellar regions associated with cognitive resources (Vingerhoets et al. 2003; Xue et al. 2004); 3) a reduction in second versus first language processing for early bilinguals (Hernandez et al. 2007) and as proficiency in the second language improves (Perani et al. 1996; Chee et al. 2001; Ding et al. 2003; Wang et al. 2003; Wartenburger et al. 2003; Xue et al. 2004; Perani and Abutalebi 2005; Meschyan and Hernandez 2006; Abutalebi et al. 2007); and 4) the influence of a reader's native language on reading activation for pseudowords (Paulesu et al. 2000) or second language words (Tan et al. 2003; Nelson et al. 2009).

Our experimental design included 2 groups of participants who both spoke Italian and English. One group comprised Italian subjects who had learnt English as a second language (mean age of acquisition = 11 years, range 9–16). The other group comprised British subjects who had learnt Italian as a second language (mean age of acquisition = 16 years, range 11–21). Both groups were scanned using the same equipment, analyses and stimuli which included written English words (with both low-frequency regular and irregular spellings), their Italian translations, and pseudowords. A baseline condition (viewing meaningless falsefonts) was included to allow assessment of activation that was common to all word types.

Second language written and oral knowledge was assessed using the Mill Hill Vocabulary scale in English for Italian subjects and in Italian for English subjects. The scores were then correlated with first and second language activation across the whole brain. This between subject correlation analysis capitalized on intersubject variability in the second language abilities of our subjects. Therefore, our within group approach is in contrast to studies of between group differences where it was necessary to minimize intersubject variability in proficiency between or within subject groups. Moreover, by looking for effects of second language knowledge on reading activation that were common to both groups of participants we were able to control for differences in the language background of the participants (Paulesu et al. 2000), for example, whether the first or second language had a spelling-to-sound mapping that was internally consistent (as in Italian) or inconsistent (as in English).

Finally, to interpret the effects of second language vocabulary knowledge on first language reading activation, we also report the effects of 1) word regularity (irregular > regular spellings) on low-frequency English words; 2) nonlexical pseudoword reading relative to familiar words with regular and irregular spellings; 3) processing load (pseudowords and irregularly spelled English words relative to regularly spelled English words); 4) second relative to first language reading; and 5) reading experience on pseudoword reading (i.e., a group comparison between those whose native language is English versus Italian). These additional analyses may provide a more detailed functional characterization of the regions showing a significant impact of second language vocabulary knowledge on first language reading activation.

## Materials and Methods

The study was approved by the National Hospital for Neurology and Institute of Neurology Medical Ethics Committee and the Institute of Psychiatry/South London and Maudsley NHS Trust Ethical Committee (Research). Written informed consent for the assessment, including MRI, was obtained from all participants.

### *Subject Details*

Two groups of participants were studied who both spoke Italian and English. The first consisted of 17 healthy right-handed volunteers (mean age 31 years, 11 females, and 6 males) with Italian as their first language, who had learnt English at a mean age of 11 (range 9–16) and lived in the UK at time of assessment. Fifteen participants had postgraduate education and 2 participants had degree level education. We refer to these subjects as the "Italian group." The second group consisted of thirteen healthy right-handed volunteers (mean age 39 years, 9 females, and 4 males) with English as their first language, who had started to learn Italian at a mean age of 16 (range 11–21) and lived in the United Kingdom at the time of assessment. Nine participants had postgraduate education and 4 participants had degree level education. We refer to these subjects as the "British group." Participants were recruited via advertisements in the University campus. The 2 groups did not differ in terms of gender distribution (Pearson Chi-square$_1$ = 0.79; $P > 0.05$); but the British group was older ($F_{29} = 13.12$; $P = 0.001$) and had started to learn Italian later than the Italian group had started to learn English ($F_{28} = 6.01$; $P = 0.02$).

Second language vocabulary knowledge was defined by the subjects' percentiles on the Mill Hill Vocabulary Scale (Raven et al. 1988), which is designed to assess the ability to master, recall and reproduce written and oral verbal information, but it does not assess knowledge of morphology, grammar or accuracy of articulation. The assessment involves 2 different tasks: 1) a definition task that requires participants to give a written meaning for each of 88 target words; and 2) a multiple choice test that requires participants to select a synonym from a choice of 6 written words, to indicate the meaning of each target word. The test score reflects the total number of correct responses on the 2 tasks. All participants completed this test in their second language. The Italian subjects were tested in English and the English subjects were tested in Italian. Both versions of the task presented the same words in a matched context following translation of the English words into Italian by the first author (C.N.), a native Italian speaker. A French translated version of the Mill Hill vocabulary scale has been previously used (Thorn et al. 2002).

Furthermore, all participants completed a self-rated proficiency test using an analogue scale (0–100, where zero equals poor and 100 equals excellent). At the end of the scanning session, participants were given a list of the words presented during the online test and were asked to mark all words in the second language (i.e., English for Italian–English speakers and Italian for English–Italian speakers) whose meanings they did not know.

### *Experimental Design*

All participants ($n$ = 30) were scanned on exactly the same blocked design protocol with 5 reading conditions and one baseline condition collected within each of 2 scanning sessions/runs. The 5 reading conditions were: 1) real English words with regular/typical spelling-to-sound correspondences (e.g., FACTOR); 2) real English words with irregular spelling-to-sound correspondences (e.g., SWORD); 3) Italian translation of the English regular words; 4) Italian translation of the English irregular words; 5) pseudowords (see appendix for full list of stimuli). We also included, 6) a baseline condition that presented false font strings created with a font that translated each alphabetic letter in the word conditions into an unfamiliar nonorthographic visual symbol matched in complexity to the letters. English words, pseudowords and falsefonts were the same as those used by Mechelli et al. (2005). Regular words, irregular words and pseudowords were matched for number of letters, syllables and bigram frequency (see Appendix for a full list of stimuli). In addition, regular words and irregular words were matched for familiarity (Coltheart 1981), imageability (Coltheart 1981), and log-transformed Hyperspace Analogue to Language (HAL) frequency norms (Lund and Burgess 1996), based on the HAL corpus, which consists of approximately 131 million words gathered across 3000 Usenet newsgroups during February 1995. Log HAL frequency ranged from 3.43 to 13.55 with a mean of 8.77 and a standard deviation of 1.69. Pseudowords were created from English words by changing the onset, the internal consonants, or the coda. Note that although the pseudowords were initially created by changing the letters in English words, we did not convey this information to the subjects, nor did we instruct them to read the pseudowords using Italian or English rules. Examples of the words and corresponding pseudowords include toast–noast; letter–lenner; and lemon–lenos. Our stimuli did not include words that were "cognates" (i.e., words that look and sound similar in both languages) or "interlingual homographs" (i.e., words that look the same but sound differently and mean differently in the first and second language). A full list of stimuli is provided in the appendix.

The letter or letter-like strings varied in length from 4 to 10 elements. They were presented in 21-s blocks of the same condition, with a stimulus onset asynchrony of 3 s and exposure duration of 750 ms followed by fixation (to a cross in the middle of the screen). There were 8 blocks per condition, presented in a counterbalanced order within subjects. Each condition was preceded by instructions: For example, a block of falsefonts was preceded by the instruction: "falsefonts."

All subjects were presented with exactly the same set conditions. However, to avoid repetition across languages, the words they read in English were not the same as the words they read in Italian. Thus, the stimuli for each word condition were divided into 2 sets (A and B). Half the English–Italian subjects read set A in English and set B in Italian, whereas the remaining English–Italian subjects read set B in English and set A in Italian. Likewise, half the Italian–English subjects read set A in English and set B in Italian, whereas the remaining Italian–English subjects read set B in English and set A in Italian.

Subjects were instructed to read the words and pseudowords covertly, pronouncing them in their head without mouth movements or voicing. There are advantages and disadvantages of this approach. Ideally, we would have preferred to have the subjects vocalize their responses aloud so that we could measure accuracy and response times directly. At the time of setting up the experiment, however, these facilities were not available and there was a general consensus that the process of opening and closing the mouth during overt speech in the scanner would lead to artifacts from head motion and susceptibility distortions from the airflow through the mouth. The advantage of the covert responses was therefore that we were able to minimize these artifacts. To ensure that each subject was attending to the stimuli in all conditions we monitored eye movements online. To ensure that each subject was able to read the words in their second language, a postscan reading test was administered so that responses to unknown words could be excluded from the group level analyses. We also excluded 4 other subjects who did not show the expected activation of occipito-temporal and premotor regions irrespective of word type. In summary, our results are based on activation for words that are known in 30 participants (17 Italian and 13 British) who all showed the expected pattern of reading activation.

Finally, we found significant effects of lexicality and regularity (Tables 3a and 3b) and second language (Table 3c) and vocabulary knowledge (Table 2a and 2b) that were consistent with previous studies thereby giving us confidence that we were tapping into the expected levels of word processing.

### Data Acquisition

A Siemens 1.5T scanner was used to acquire both $T_1$ anatomical volume images (1 × 1 × 1.5 mm voxels) and $T_2$*-weighted echoplanar images (64 × 64, 3 × 3 mm pixels, time echo [TE] = 40 ms) with blood-oxygenation-level–dependent (BOLD) contrast. Each echoplanar image comprised 35 axial slices 2 mm thick with 1-mm slice interval, and 3 × 3 mm in plane resolution. For each subject, a total of 372 volume images were taken into 2 separate runs, with an effective repetition time (TR) of 3.15 s/volume, the first 6 (dummy) volumes being discarded to allow for $T_1$ equilibration effects.

### fMRI Data Analysis

Preprocessing was performed using SPM2 software (Wellcome Department of Imaging Neuroscience, London, UK), running under Matlab 6.5 (Mathworks, Sherbon, MA). All volumes from each subject were realigned using the first as reference and resliced with sinc interpolation. The functional images were spatially normalized to a standard MNI-305 template (Montreal Neurological Institute, ICBM NIH P-20 project) using a total of 1323 nonlinear-basis functions (Friston et al. 1995). Functional data were spatially smoothed with a 6-mm full width at half maximum isotropic Gaussian kernel to compensate for residual variability in functional anatomy after spatial normalization and to permit application of Gaussian random-field theory for adjusted statistical inference.

First level statistical analyses were performed in a subject-specific fashion using an event-related approach. There were 6 different regressors corresponding to the 6 different conditions (see above). Each of these regressors was derived from the onset times of each stimulus in that condition. To exclude unknown words from the second language word conditions, our word regressors only included the onsets of words whose meanings and pronunciations were known in the postscan test. All the words that were not known in the post hoc test were treated as errors and modeled as a seventh regressor in the first level analysis which was excluded from all subsequent second level analyses. Each first level regressor was modeled independently by convolving the onset times for each stimulus with a synthetic hemodynamic response function (HRF, with no dispersion or temporal derivatives). The parameter estimates were calculated for all brain voxels using the general linear model. To remove low-frequency drifts, the data were high-pass filtered using a set of discrete cosine basis functions with a cutoff period of 156 s. At the first level, the statistical contrasts compared each of the reading conditions to falsefonts (i.e., the baseline). This resulted in 5 contrast images that corresponded to activation related to reading: 1) English words with irregular spellings, 2) English words with regular spellings, 3) the Italian translations of English words with irregular spellings, 4) the Italian translations of English words with regular spellings, and 5) pseudowords. Note that all Italian translations of English irregular words have spelling-to-sound correspondences that are regular in Italian.

### Second Level Analyses at the Group Level

A second level 2-way ANOVA with 10 conditions was computed in SPM5 to identify word-type and language effects within subject group. The first factor was subject group (English–Italian or Italian–English). The second factor was the 5 reading conditions. In other words, each subject contributed 5 contrasts which were modeled separately for each subject group with a correction for nonsphericity. This resulted in a total of 10 different conditions. Within the same analysis, second language vocabulary knowledge, as defined by the subjects' percentiles on the Mill Hill Vocabulary Scale (Raven et al. 1988), was modeled as a covariate that interacted with each of the 10 conditions. This enabled us to extract the effect of second language vocabulary knowledge on reading words in the first language, the second language and pseudowords. For each contrast of interest, the effects were computed over all subjects (the main effects), for the British group only and for the Italian group only.

### Other Effects

To interpret the results, we also conducted a series of "other analyses" to identify the effects of:

1) Spelling-to-sound regularity by comparing activation for reading English words with irregular versus regular spellings;
2) Pseudoword reading by comparing activation for reading pseudowords versus first language words;
3) Processing load by comparing pseudowords and irregularly spelled English words versus regularly spelled English words; and
4) Second language reading by comparing second language word conditions for the 2 groups (English–Italian and Italian–English) with both first language word conditions.
5) Group differences between our English–Italian and Italian–English subjects for pseudoword reading only. The focus on pseudoword reading avoided confounds from proficiency differences in first and second language reading and allows us to test previously reported differences between English versus Italian subjects reading pseudowords (Paulesu et al. 2000).

### "Predictions for Other Effects"

Our predictions for the English–Italian subjects were based on the results of a previously reported study that presented British subjects the identical English word, pseudoword and false font conditions (Mechelli et al. 2005). Specifically, this study reported:

a) Effects of spelling-to-sound regularity (English words with irregular versus regular spellings) in the ventral part of left pars triangularis (–52, 34, 4) extending into the pars orbitalis and an anterior region in the left occipito-temporal sulcus (–42 –42 –18).
b) Pseudoword reading (pseudowords versus all English words) in the left dorsal premotor cortex (–56 0 40) and a posterior region in the left occipito-temporal sulcus (–46 –60 –18).
c) Effects of processing load (pseudowords and irregularly spelled English words versus regularly spelled English words) in the left pars opercularis (–54 +8 +18) and the left occipito-temporal sulcus (–46 –54 –18).

With respect to 4) the effect of second language reading (second vs. first language), we predicted increased activation in left frontal and right cerebellar regions (Xue et al. 2004; Yokoyama et al. 2006).

With respect to 5) group differences in pseudoword reading for English–Italian and Italian–English subjects, our predictions were based on a study by Paulesu et al. (2000) that reported greater pseudoword reading activation in the left posterior temporal cortex ($x = -46$, $y = -34$, $z = +16$; $Z$ score = 2.6) for Italian than English subjects and the left posterior inferior temporal cortex ($x = -58$, $y = -58$, $z = -14$; $Z$ score = 2.7) and the left pars opercularis ($x = -46$, $y = +18$, $z = +20$; $Z$ score = 2.7) for English relative to Italian subjects.

### *Statistical Thresholds*

To identify the effect of second language vocabulary knowledge on reading activation, we used standard procedures in SPM5 to set the significance level to $P < 0.05$ after family wise error correction for multiple comparisons across the whole brain. In addition, we lowered the threshold to $P < 0.05$ uncorrected in the areas that Mechelli et al. (2005) reported for word-type differences when the identical English word, pseudoword and false font conditions were presented to British subjects. To do this we searched for effects that were within 6 mm of the inferior frontal co-ordinates (see above). For completeness, we also report the number of voxels for each effect at $P < 0.001$ and $P < 0.05$ uncorrected.

## Results

### *Behavioral Data*

We report 3 different behavioral measures (see Table 1): Second language vocabulary knowledge, self-rated proficiency and the postscanning reading test of the items seen in the scanner. Although there was no significant group difference in either accuracy ($F_{29} = 0.30$, $P > 0.05$) or completion time ($F_{29} = 0.36$, $P > 0.05$) on the second language vocabulary test, there was wide variance within group. This allowed us to examine the effect of second language vocabulary knowledge on regional activations within group. Self-rated proficiency was assessed using an analogue scale (0–100), where zero equals poor and 100 equals excellent. On this test, English–Italian speakers rated themselves as less proficient than the Italian–English speakers ($F_{29} = 11.58$, $P < 0.01$). Likewise, in a postscanning reading test, English–Italian speakers reported more second language words as unknown than the Italian–English speakers ($F_{29} = 14.42$, $P < 0.001$). The present paper is not concerned with these between group differences because our focus is on 1) the correlation of second language vocabulary knowledge on regional activation within group, and 2) the consistency of this effect across 2 groups with different reading experience.

**Table 1**
Summary of behavioral data for both subject groups

| | Italian group Mean (SD) | British group Mean (SD) |
|---|---|---|
| Mill Hill age-matched percentile[a] | 60.7 (24.2) | 54.8 (27.9) |
| Mill Hill completion time (in min) | 15.1 (5.4) | 16.4 (6.7) |
| Self-rated proficiency in the second language | 75.8 (12.1) | 54.8 (21.3) |
| Unknown second language words on postscan test | 2.6% (3.3) | 10.9 (8.1) |
| Percent of errors for English regular words | 2.5% (3.9) | |
| Percent errors for English irregular words | 2.8% (4.4) | |

[a]The Mill Hill age-matched percentile is based on normative values in native English speakers. Although the British group knew fewer words in their second language, this potential confound for a between group comparison is not relevant to the results reported in this paper which focuses on within group variance that is common to both groups.

### *fMRI Data*

*The Effect of Second Language Vocabulary Knowledge on First Language Reading Activation*

#### *Whole-Brain Analysis*

There was one highly significant finding: better second language vocabulary knowledge was associated with increased first language reading activation in the left pars orbitalis (Fig. 1 and Table 2a). This effect was observed in both the British ($Z = 4.8$, $P < 0.001$) and Italian subjects ($Z = 2.8$, $P < 0.005$). It was therefore replicated across languages that had both consistent and inconsistent spelling-to-sound relationships, see Table 2a for details.

There was no significant effect of second language vocabulary knowledge on second language reading or pseudoword reading ($P > 0.05$ uncorrected).

#### *Regions of Interest for the Effect of Second Language Vocabulary Knowledge*

Taking a regions of interest approach, we then examined how second language vocabulary knowledge was related to activation in the left dorsal premotor ($x = -56$, $y = 0$, $z = +40$) and left pars opercularis ($x = -54$, $y = +8$, $z = +18$) regions that Mechelli et al. (2005) associated with nonlexical (pseudoword) reading and processing load (pseudoword and irregularly spelled English words relative to regular words) respectively. In the left dorsal premotor region, we found a positive correlation between higher second language vocabulary knowledge and activation for reading all words (first and second language) and pseudowords (see Fig. 2 and Table 2b). In contrast, in the left pars opercularis, we found a negative correlation such that higher second language vocabulary knowledge in British subjects was associated with decreased activation for reading second language words ($x = -60$, $y = +8$, $z = +24$; $Z$ score = 2.7 with 52 voxels at $P < 0.05$ uncorrected) but this effect was not highly significant in the British group and not replicated in the Italian group.

#### *Summary*

In summary, the effect of second language vocabulary knowledge had different effects in the left pars orbitalis (a significant positive effect for first but not second language reading), the left dorsal premotor cortex (a positive effect for both first and second language reading) and the left pars opercularis (decreased activation for second language reading in British participants).

*Other Effects*

*The effect of English word regularity in both groups of subjects.* Activation in the left pars orbitalis was higher for English words with irregular than regular spellings (see Table 3a). The observation enables us to functionally localize the left pars orbitalis area associated with lexical/semantic reading within our own participants, and shows that it is this area where increased second language vocabulary knowledge increased first language reading activation (see Table 2a and Fig. 1). There were no other effects of regularity that were significant ($P < 0.05$ corrected) in the whole-brain analysis, however, as predicted on the basis of Mechelli et al. (2005), we also observed increased activation for irregular words in an anterior region of the occipito-temporal sulcus (see Table 3a).

*Pseudoword reading.* Activation for reading pseudowords compared with familiar, first language words identified the left dorsal premotor cortex (see Table 3b). This area corresponds to that where reading activation increased with second

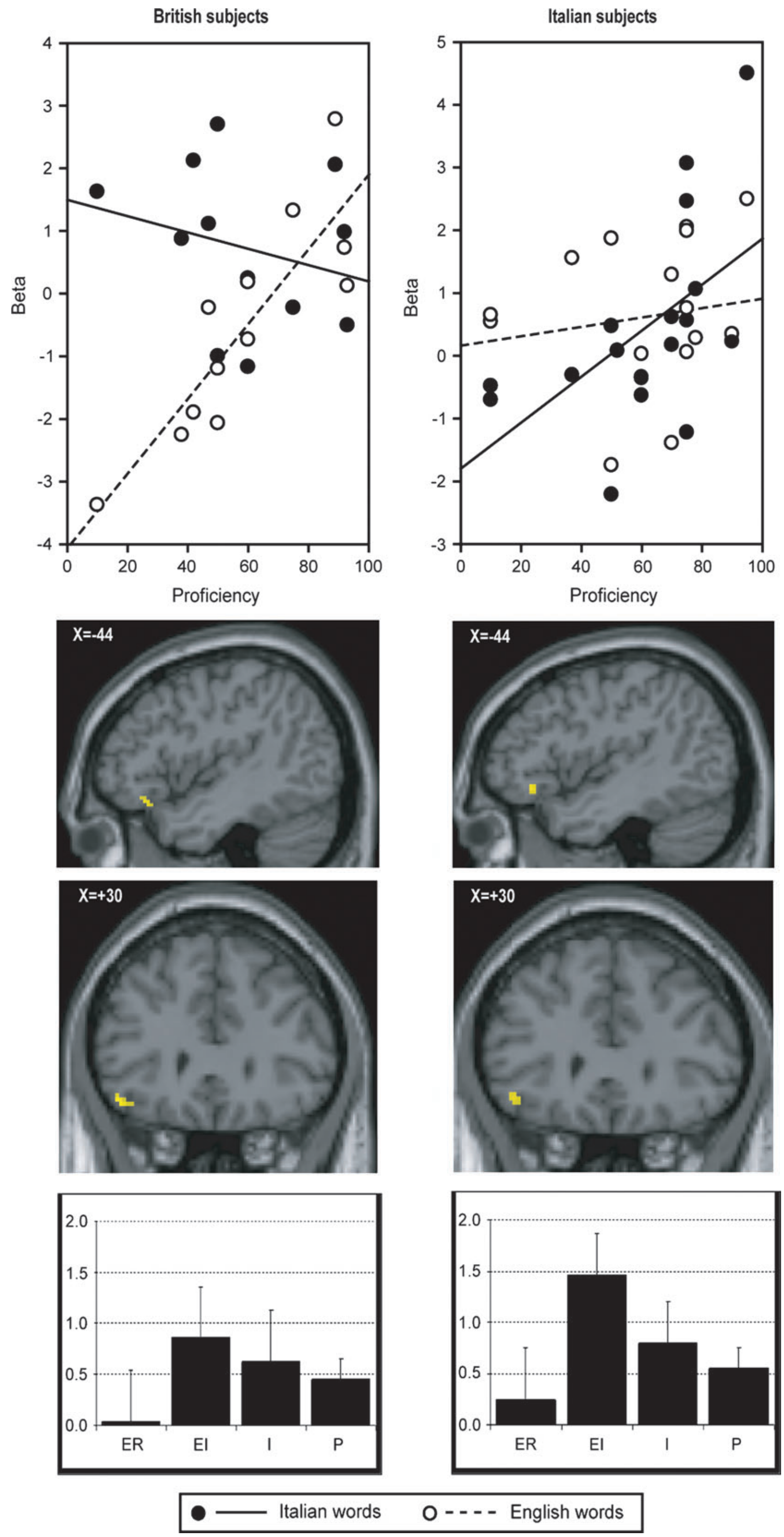


**Figure 1.** The effect of second language vocabulary knowledge on first language reading activation in the left pars orbitalis. Top. The correlation between second language vocabulary knowledge and activation for reading in Italian (continuous line) and English (dotted line) is shown separately for British and Italian subjects in the left pars orbitalis at $x = -44$, $y = +30$, $z = -14$. Activation is summed over regular and irregular English words because the effects were consistent for both. The $R$ values for the correlation between second language proficiency and first language reading were 0.86 ($P < 0.001$) for the British group and 0.54 ($P < 0.005$) for the Italian group. Consistent with prior studies, the correlations in both groups show left pars orbitalis activation is higher for second than first language reading when second language vocabulary knowledge is low but not when it is high. Contrary to previous claims, however, this effect was driven by changes in first rather than second language processing. Middle: Sagittal and coronal brain slices showing the anatomical location of the correlation between second language proficiency and first language reading thresholded at $P < 0.01$ uncorrected for both groups. See Table 2a for details of the exact location, $Z$ scores and extent. Below: The effect size for each condition relative to falsefonts in

**Table 2**

The effect of second language vocabulary knowledge on reading activation (excluding irregular words)

| a) In left pars orbitalis (whole-brain analysis) | Over groups | | | British group | | | Italian group | | |
|---|---|---|---|---|---|---|---|---|---|
| | *x, y, z* | *Z* | $V^{001}$ | *x, y, z* | *Z* | $V^{001}$ | *x, y, z* | *Z* | $V^{05}$ |
| First language reading: all | −48, 38, −12 | 4.4 | 163 | −48, 38, −14 | 4.8 | 65 | −44, 32, −10 | 2.8 | 155 |
| | −48, 38, −10 | 3.7 | 21 | −48, 38, −12 | 4.2 | 25 | N/A | N/A | N/A |
| First > second language | −46, 40, −14 | 4.2 | 153 | −46, 40, −16 | 4.6 | 97 | −50, 40, −6 | 3.8 | 126 |
| | −48, 38, −10 | 3.3 | 8 | −48, 38, −12 | 3.4 | 15 | −50, 30, −6 | 2.5 | 32 |
| First language> pseudowords | −46, 40, −14 | 5.3 | 114 | −48, 38, −14 | 5.6 | 89 | −40, 34, −8 | 2.9 | 127 |
| | −46, 38, −12 | 4.0 | 41 | −48, 38, −12 | 4.4 | 32 | N/A | N/A | N/A |
| First language > all | −46, 40, −14 | 5.0 | 295 | −46, 40, −14 | 5.3 | 130 | −50, 40, −8 | 3.7 | 165 |
| | −48, 38, −12 | 4.2 | 45 | −48, 38, −12 | 3.9 | 20 | N/A | N/A | N/A |
| b) In dorsal premotor cortex *(ROI = −56 0 40)* | Over groups | | | British group | | | Italian group | | |
| | *x, y, z* | *Z* | $V^{05}$ | *x, y, z* | *Z* | $V^{05}$ | *x, y, z* | *Z* | $V^{05}$ |
| All reading | −56, 0, 40 | 3.1 | 69 | −54, 4, 38 | 3.1 | 412 | −56, −2, 40 | 2.5 | 29 |
| | −54, 2, 40 | 3.0 | 102 | −54, 4, 38 | 3.2 | 119 | N/A | N/A | N/A |
| First language reading | −52, 2, 44 | 2.9 | 110 | −52, 2, 44 | 2.6 | 411 | −58, −2, 40 | 2.2 | 12 |
| | −56, 0, 42 | 2.2 | 31 | −54, 4, 38 | 2.0 | | N/A | N/A | N/A |
| Second language reading | −56, 0, 40 | 3.1 | 111 | −54, 4, 38 | 3.1 | 178 | −54, −2, 40 | 2.5 | 40 |
| | −54, 4, 38 | 3.0 | 188 | N/A | N/A | | −56, −2, 40 | 2.1 | 31 |
| Pseudoword reading | −56, 0, 40 | 3.1 | 72 | −56, 2, 38 | 3.0 | 36 | −56, 2, 38 | 2.3 | 70 |

Note: (a) In left pars orbitalis from the whole-brain analysis and (b) in left dorsal premotor cortex from the region of interest analysis (within 6 mm of co-ordinates [$x = -56$, $y = 0$, $z = 40$] from Mechelli et al., 2005). $V^{001}$ = Number of voxels at $P < 0.001$ uncorrected. $V^{05}$ = Number of voxels at $P < 0.05$ uncorrected. *Z* scores greater than 3.0 are significant at $P < 0.001$; *Z* scores greater than 1.64 are significant at $P < 0.05$. *Z* scores and voxel counts in bold are those that were significant after correction for multiple comparisons across the whole brain for height ($Z > 4.8$) or extent (>90 voxels at $P < 0.001$).



language vocabulary knowledge (see Table 2b). There were no other effects of pseudoword reading that were significant ($P < 0.05$ corrected for multiple comparisons across the whole brain), however, as predicted on the basis of Mechelli et al. (2005), we also observed increased activation for pseudowords in a posterior region of the occipito-temporal sulcus (see Table 3b).

*The effects of processing load.* Activation for pseudowords and irregularly spelled English words versus regularly spelled English words increased activation in the left pars opercularis and a mid region of the occipito-temporal sulcus (see Table 3c). In addition the whole-brain analysis ($P < 0.05$ corrected) identified a significant effect of processing load in the right cerebellum and left putamen.

*The effect of reading in a first versus second language in both groups of subjects.* Consistent with previous studies, activation in the left pars opercularis, left dorsal premotor cortex and right cerebellum was significantly higher for reading in a second language than reading in a first language (Table 3d). There were no other effects of first versus second language reading that were significant ($P < 0.05$ corrected) in the whole-brain analysis in either subject group.

*Group differences in pseudoword reading for English–Italian and Italian–English subjects.* There were no effects that were significant ($P < 0.05$ corrected) in the whole-brain analysis. When we explored how activation for pseudoword reading depended on subject group in the areas reported by Paulesu et al. (2000), we only observed a weak trend in the left posterior inferior temporal cortex ($x = -58$, $y = -60$, $z = -14$; *Z* score = 2.3) for English–Italian relative to Italian–English subjects. We did not replicate the other effects reported by Paulesu et al. (2000) in the left pars opercularis ($x = -46$, $y = +18$, $z = +20$) for English relative to Italian subjects or the left posterior temporal cortex ($x = -46$, $y = -34$, $z = +16$) for Italian relative to English subjects.

## Discussion

Many previous functional imaging studies have shown that left frontal activation increases for second relative to first language processing. This effect is typically attributed to increased computational demands in the less familiar language (see Perani and Abutalebi 2005 for a review), but very little is known about the impact of second language learning on first language reading activation. Our prediction was that second language learning would modulate first language reading activation in 2 different ways. First, it would increase the demands on nonlexical spelling-to-sound conversion because knowing 2 languages increases the number of sounds associated with the same letter combination. Second, we predicted that, as a consequence of increased ambiguity in spelling-to-sound mappings, first language reading would become more reliant on lexical/semantic processing.

We investigated these predictions using fMRI. This allowed us to localize, within each group of participants, the brain regions that were differentially involved in nonlexical reading, lexical/semantic reading and processing load when nonlexical and lexical/semantic processing are inconsistent. Nonlexical reading areas were those that were more activated for reading pseudowords than words, lexical/semantic reading areas were those that were more activated for reading low-frequency irregularly spelled words than regularly spelled words, and areas associated with processing load were those that were commonly activated by pseudowords and low-frequency

the region showing an effect of second language vocabulary on first language reading. ER = English regularly spelled words. EI = English irregularly spelled words, I = Italian words and P = pseudowords. This plot shows that activation in this region was highest for irregularly spelled English words in both groups of subjects, consistent with a role in lexical/semantic reading.

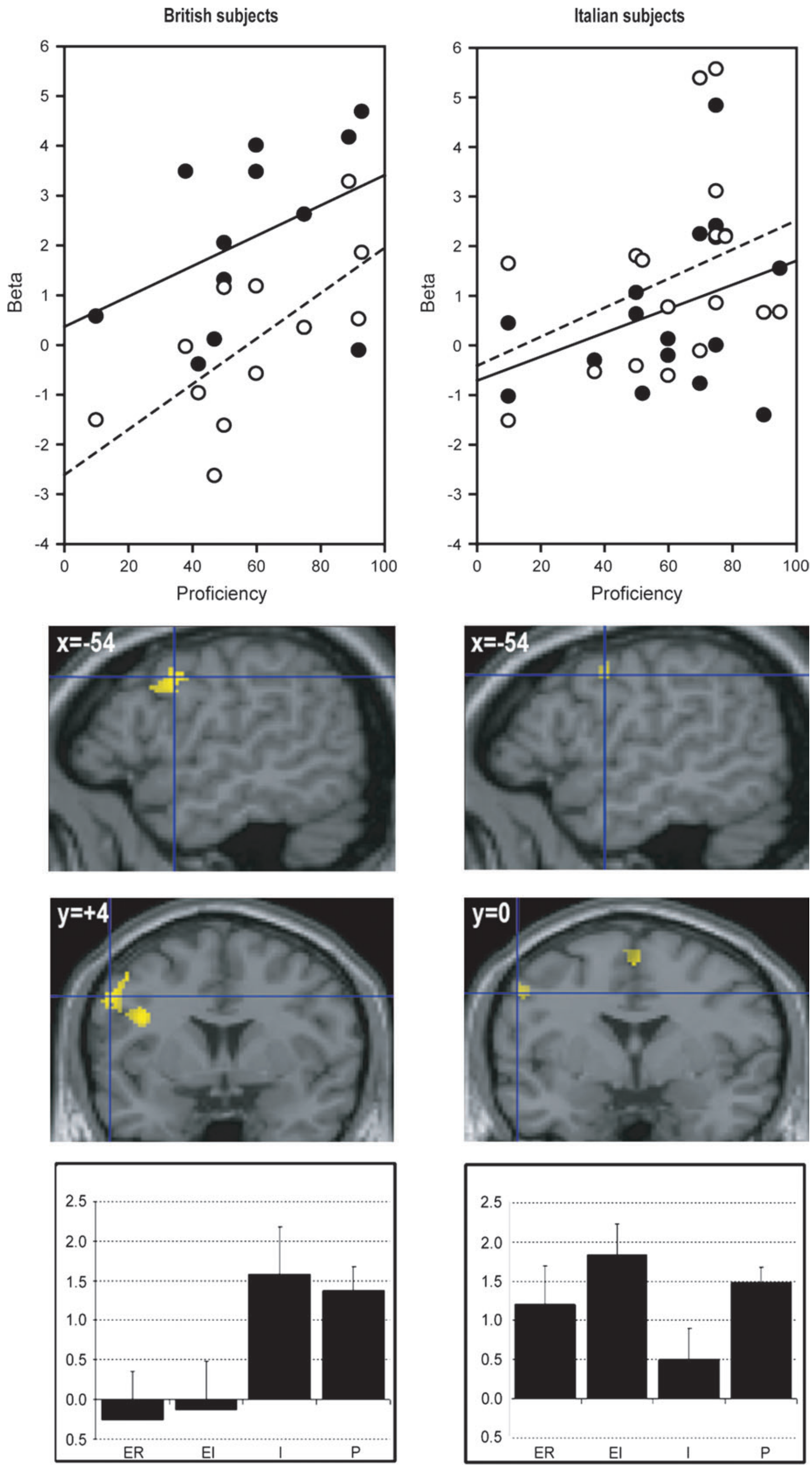


**Figure 2.** The effect of second language vocabulary knowledge on left dorsal premotor activation. Top. The correlation between second language vocabulary score and activation for reading in Italian (continuous line) and English (dotted line) is shown separately for British and Italian subjects in the left dorsal premotor cortex at $x = -52$, $y = +2$, $z = +44$ and $x = -54$, $y = -2$, $z = +42$, respectively. These co-ordinates corresponded to the local maxima in the left premotor cortex for the correlation of second language vocabulary score and reading activation summed over first and second language conditions. The $R$ values for the correlation between second language vocabulary score and reading activation were 0.68 ($P < 0.001$) for the British group and 0.38 ($P < 0.05$) for the Italian group in the first language; and 0.41 ($P < 0.005$) for the British group and 0.36 ($P < 0.05$) for the Italian group in the second language. Middle: Sagittal and coronal brain slices showing the anatomical location of the correlation between second language proficiency and reading activation (summed over first and second language), thresholded at $P < 0.05$ uncorrected for both groups. See Table 2b for details of the exact location, $Z$

**Table 3**
Predicted other effects

| a) Irregular > regular (whole-brain analysis) | Over groups | | | British group | | | Italian group | | |
|---|---|---|---|---|---|---|---|---|---|
| | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{001}$ |
| Left pars orbitalis | −38, 32, −6 | 5.0 | 119 | −40, 32, −6 | 3.5 | 8 | −36, 30, −4 | 5.0 | 93 |
| | −38, 44, −10 | 3.1 | | −38, 44, −10 | 2.3 | | −50, 38, −12 | 3.8 | |
| | −48, 36, −12 | 3.1 | | −48, 34, −14 | 1.6 | | −40, 40, −14 | 3.0 | |
| Left anterior O.T.s (ROI = −42 −42 −18) | −46, −48, −16 | 3.5 | 32 | −40, −46, −12 | 4.9 | 136 | −42 −38 −14 | 2.0 | 0 |
| b) Pseudoword reading | Over groups | | | British group | | | Italian group | | |
| | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{001}$ |
| Left dorsal premotor cortex (ROI = −56 0 40) | −46, 0, 32 | 5.6 | 426 | −52, 6, 36 | 4.1 | 237 | −46, 0, 34 | 4.0 | 177 |
| | −50, 4, 40 | 4.0 | | −48, −2, 44 | 2.3 | | −50, 0, 40 | 3.3 | |
| Left posterior O.T.s. (ROI = −46 −60 −18) | −50, −60, −18 | 4.3 | 51 | −52, −60, −18 | 4.1 | 22 | −46, −58, −14 | 3.6 | 7 |
| c) Processing load | Over groups | | | British group | | | Italian group | | |
| | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{05}$ |
| Left pars opercularis (ROI = −54 8 18) | −60, 12, 14 | 4.3 | 41 | −60, 12, 14 | 4.2 | 22 | −50, 8, 14 | 3.1 | 254 |
| Left mid O.T.s (ROI = −46 −54 −18) | −44, −52, −12 | 4.1 | 51 | −44, −54, −12 | 4.4 | 22 | −46, −54, −16 | 2.5 | 90 |
| Right cerebellum | 28, −64, −32 | 4.8 | 159 | 28, −64, −32 | 3.8 | 24 | 32, −60, −30 | 3.6 | 44 |
| Left putamen | −24, 2, −2 | 4.9 | 135 | −24, 2, −2 | 4.9 | 91 | −24, 0, 2 | 2.1 | 7 |
| d) Second > first language (whole-brain analysis) | Over groups | | | British group | | | Italian group | | |
| | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{001}$ | *x*, *y*, *z* | *Z* | $V^{001}$ |
| Left dorsal premotor cortex | −48, 2, 34 | 5.6 | 865 | −44, 2, 30 | 4.5 | 245 | −48, 0, 36 | 4.8 | 77 |
| | −50, 0, 40 | 4.3 | | 52, 2, 40 | 3.5 | | −50, 0, 40 | 3.3 | |
| Left pars opercularis | −56, 10, 10 | 5.5 | | −56, 10, 10 | 4.3 | 84 | −56, 10, 10 | 3.6 | 41 |
| | −56, 8, 20 | 5.1 | | −56, 8, 20 | 3.7 | | −60, 6, 28 | 4.3 | |
| Right cerebellum | 34, −68, −30 | 5.2 | 139 | 32, −60, −30 | 3.9 | 7 | 32, −58, −34 | 4.3 | 73 |

Note: Anatomical location (in MNI co-ordinates) and *Z* score (*Z*) for (a) reading irregular > regular words (i.e., activation for English words with irregular spellings relative to English words with regular spellings; (b) pseudowords reading (i.e., activation for pseudowords relative to first language words; and (c) Processing load (i.e., activation for pseudowords and irregularly spelled English words relative to regularly spelled English words); and (d) second > first language (i.e., Italian > English in English subjects and English > Italian in Italian subjects). $V^{001}$ = Number of voxels at $P < 0.001$ uncorrected. $V^{05}$ = Number of voxels at $P < 0.05$ uncorrected. *Z* scores greater than 3.0 are significant at $P < 0.001$; *Z* scores greater than 1.64 are significant at $P < 0.05$. *Z* scores and voxel counts in bold are those that were significant after correction for multiple comparisons across the whole brain for height ($Z > 4.8$) or extent (>90 voxels at $P < 0.001$). $P > 0.05$ uncorr = not significant even when threshold is lowered to $P < 0.05$ uncorrected.

irregular words. Localizing these word-type effects helped to interpret the effect of second language vocabulary knowledge on first language reading.

Consistent with previous fMRI studies that have directly compared pseudowords to English irregularly spelled words (Binder et al. 2005; Mechelli et al. 2005), we identified increased activation for nonlexical reading in the left dorsal premotor cortex (see Table 3b) and increased activation for lexical/semantic reading in the left pars orbitalis (see Table 3a). Also consistent with previous studies, both these areas were significantly more activated for second than first language reading (see Perani and Abutalebi 2005). These effects validated our experimental design and provided a robust context for demonstrating 2 novel effects of interest: 1) Evidence that first language reading involves more lexical/semantic processing when a second language with the same alphabet is learnt was demonstrated by increased left pars orbitalis activation with greater second language vocabulary knowledge. 2) Evidence that learning to read a second language increased the demands on nonlexical spelling-to-sound conversion was provided by the demonstration that, as second language vocabulary knowledge increased, left dorsal premotor activation increased for reading in the first as well as the second language. Interestingly, we did not observe a positive correlation between second language vocabulary knowledge and reading activation in the left pars opercularis associated with processing load. Therefore, there was no evidence to suggest that second language knowledge increased interference between nonlexical and lexical/semantic processing.

Our results are important for understanding the impact of learning a second language. As shown previously, prefrontal activation is higher for a second relative to first language and this diminishes as second language proficiency increases (see Fig. 1; Perani et al. 1996; Kim et al. 1997; Ding et al. 2003; Wang et al. 2003; Wartenburger et al. 2003; Perani and Abutalebi 2005; Meschyan and Hernandez 2006). The standard explanation for this observation is that second language activation diminishes with increased proficiency because second language processing becomes less demanding (Xue et al. 2004). Our finding that the effect of proficiency in the left pars orbitalis is primarily driven by changes in the processing of the first rather than the second language processing (see Fig. 1) offers an additional explanation. Specifically, we propose that first language activation increases with second language proficiency and this has the effect of decreasing activation differences between the second and first languages (see Fig. 1). We found evidence to support this hypothesis in both the left pars orbitalis and the left dorsal premotor cortex. In contrast, there was a trend for activation in the left pars opercularis to decrease with second language knowledge. All together, the results suggest that the previously observed reduction in activation differences between the second and first language as proficiency improves is the result of both decreased activation in the second language (in the left pars

score and extent. Below: The effect size for each condition relative to falsefonts in the region showing an effect of second language vocabulary on reading all types of words. ER = English regularly spelled words. EI = English irregularly spelled words, I = Italian words and P = pseudowords. This plot shows that activation in this region was higher for pseudowords than first language words in both groups of subjects, consistent with a role in nonlexical reading.

opercularis) as well as increased activation in the first language (in the pars orbitalis and premotor regions).

It may be relevant to note that the effect of second language proficiency was stronger in the British than Italian subjects. This might reflect the less consistent spelling-to-sound relationships in English, even for regularly spelled words. However, we cannot interpret group differences in this study because the range of proficiency was wider in the British group than the Italian group and this may affect the sensitivity of the correlation analyses in the British relative to Italian group. The critical point is that group differences do not undermine our conclusion that second language vocabulary was positively correlated with first language reading activation in the left pars orbitalis and this effect was observed irrespective of whether the first language had a consistent or inconsistent spelling-to-sound relationship.

We have argued that activation in the left pars orbitalis reflects the demands on lexical/semantic reading because this area is more activated for irregular words than pseudowords in this and previous studies (Table 3a; Binder et al. 2005; Mechelli et al. 2005). The left pars orbitalis has also been associated with the retrieval of semantic information (Poldrack et al. 1999; Badre et al. 2005; Wagner et al. 2000; Badre and Wagner 2007), working memory (Sabb et al. 2007) and semantic interference during naming (de Zubicaray et al., 2006) and reading (Mechelli et al. 2007). Together the prior literature suggests that activation in the left pars orbitalis is related to executive control functions rather than semantic associations per se. In this context, we suggest that activation in the left orbitalis for first language reading is an adaptive response to increased inconsistency in the mapping of letters to sounds. Such inconsistency, and the interference induced, increases with second language vocabulary knowledge. Left orbitalis activation helps control this interference and so fulfils an executive control function. This view is compatible with prior behavioral (Van Wijnendale and Brysbaert 2002; Brysbaert and Dijkstra 2006; Smits et al. 2006) and neuroimaging studies (e.g., Rodriguez-Fornells et al. 2002, 2005) showing that bilingual speakers cannot restrict access to words in their other language and need to control lexical interference between languages particularly when both languages are in active use (Abutalebi et al. 2008).

### *Word-Type Effects*

By comparing reading activation for pseudowords, low-frequency irregularly spelled English words and low-frequency regularly spelled English words, we have replicated the dissociation of 3 different reading systems that were previously identified by Mechelli et al. (2005). Specifically, like Mechelli et al. (2005), we show that during reading, 1) a region in the left posterior occipito-temporal sulcus shows the same pattern of response to that in the left premotor cortex (i.e., more activation for pseudowords than irregular words) consistent with nonsemantic reading; 2) a region in the left anterior occipito-temporal sulcus shows the same pattern of response as that in the left ventral inferior frontal cortex (i.e., more activation for irregular words than pseudowords) consistent with lexico-semantic reading; and 3) a region in a middle region of the left occipito-temporal sulcus shows the same pattern of response as that in the left pars opercularis (i.e., more activation for pseudowords and irregular words than regular words) consistent with processing load. This is the first replication of the dissociation of these 3 reading systems.

As Italian is a consistent language, it is less easy to dissociate lexical/semantic and nonlexical reading because there are no irregularly spelled words and a comparison of regularly spelled words to pseudowords typically results in greater activation for pseudowords in all frontal regions (see Mechelli et al. 2003 for a review). Consequently, to identify lexical/semantic reading areas in our Italian participants, we compared activation for irregular and regularly spelled English words. Remarkably, activation for Italian subjects reading English words with irregular versus regular spellings corresponded to that observed in the English participants (i.e., increased left pars orbitalis activation), even though the Italians were reading in their second language. This demonstrates that the Italians had learnt and were actively using a second set of spelling-to-sound relationships despite the covert nature of the task. Thus, our findings are consistent with the hypothesis that spelling-to-sound associations are increased by second language reading experience.

By investigating the effect of word type and second language processing in the same study, we are also able to report that second relative to first language processing increases activation in areas that are associated with pseudoword reading and processing load within language. This allows us to segregate the different types of processes that are more demanding in a second language. For example, second relative to first language activation in the left premotor cortex may be a consequence of poor lexical/semantic mediation due to less familiarity with second relative to first language words. In contrast, second relative to first language activation in the left pars opercularis, right cerebellum and left putamen may reflect interference at the level of word selection. We found these regions were more activated for pseudowords and irregular words relative to regular words, whereas other studies have observed activation in the same regions for second relative to first language processing (Klein et al. 1999; Xue et al. 2004).

### *Other Questions*

Given that we investigated reading activation in relatively large samples of English and Italian subjects, why were we unable to replicate previous findings by Paulesu et al. (2000) that native language experience determines the pattern of brain activation during pseudoword reading? There are 2 possible answers that require further investigation. First, our bilingual subjects were required to switch back and forth between reading in English and reading in Italian. Behavioral studies have shown that reading strategies depend on the context (Zevin and Balota 2000; Raman et al. 2004) and so this procedure may have overridden learning biases that were observed in Paulesu et al.'s (2000) subjects reading in one language. Second, it is also possible that differences between pseudoword reading in Italian and English readers reflect false positives because the $Z$ scores reported by Paulesu et al. (2000) were only significant at $P < 0.01$ uncorrected, did not survive a correction for multiple comparisons and were based on fixed effect rather than random effect analyses. Future studies are therefore required to replicate differences in pseudoword reading previously observed in Italian and English subjects and to determine whether group differences in pseudoword reading activation are greater in monolingual than bilingual subjects.

Finally, we note that future studies are required to investigate how well the results of our fMRI study might generalize to everyday word processing in a range of different languages. In our attempts to control and constrain our experimental design, our bilingual participants performed a very un-naturalistic task. They read a series of unrelated single words and had to switch between languages on a minute-by-minute basis. Our results might therefore be restricted to a dual language context (i.e., when bilinguals are in a bilingual mode, Grosjean 2001) whether in the laboratory or the real-world. Previous behavioral data from moderately proficient second language speakers have shown that spelling-to-sound correspondences in the second language affect word naming in the first language only if words have recently been named in the second language (Jared and Kroll 2001) though whether this contingency is a prerequisite for an effect in highly proficient speakers is unknown. Our study prompts 2 further questions. Is the adaptive effect on first language reading that we have observed still present when bilinguals only read in their first language? What is the nature of any adaptive effects on first language reading when individuals learn to read in a second language that places very different demands on orthographic processing (e.g., Italian and Chinese)? Whatever, the answers to these questions, our data demonstrate for the first time a dynamic neural change in the processing of words in the first language.

## Conclusion

To conclude, we have demonstrated that the ability to read in 2 or more languages involves a reallocation of resources within distinct processing pathways. Specifically, it involves the processing of 2 inconsistent sets of phonological associations which increases the demands on both lexical/semantic and nonlexical retrieval routes. This is entirely consistent with the predictions from well-established cognitive models of first language reading (Plaut et al. 1996). However, the effect of second language learning on the neuronal pathways for first language reading has not previously been shown.

## Funding

Wellcome Trust and grant (MH64445) from the National Institute of Health.

## Notes

We thank Jay McClelland for useful discussions of the data.

*Conflict of Interest*: None declared.

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