## Introduction

Whether reading and spelling rely on the same orthographic memory representations has been a subject of intense controversy in the neuropsychology literature. In general, *associations* between patterns of alexia and agraphia in neurological patients have been interpreted to support the view that reading and spelling share the same orthographic lexicon. By contrast, *dissociations* between reading and spelling profiles are considered as evidence for the existence of separate orthographic input and output lexicons subserving written word recognition and production.

Recently, imaging techniques such as PET and fMRI have made it possible to localize specific brain regions involved in different language functions in healthy individuals. Specifically, imaging studies of reading have shown activations in the "visual word form area" (VWFA) occupying the mid-lateral portions of the left fusiform gyrus (BA 37), suggesting that this cortical region may be the neural substrate of the orthographic lexicon (Cohen et al., 2000; Cohen, Lehéricy, Chochon, Lemer, Rivaud & Dehaene, 2002). Critically, it has been shown that spelling words also activates the VWFA (Nakamura et al., 2000; Nakamura et al., 2002; Beeson et al., 2003). These findings seem to confirm the central role of the VWFA in orthographic processing and support the view that the same orthographic representations mediate reading and spelling. Unfortunately, the available neuroimaging evidence on the relationship between reading and spelling is limited in that the relevant studies involved different subject groups as well as different languages. In fact, there has been no imaging study to date that explored both reading and spelling in the same group of subjects.

The purpose of this study was to use a within-subjects fMRI design to investigate whether the cortical region responsible for orthographic processing in reading is also activated during spelling. Specifically, we hypothesized spatially overlapping patterns of neural activation in the cortical region corresponding to the VWFA would support shared component models of written language processing that postulate a single orthographic lexicon subserving both reading and spelling.

## Methods

Subjects: Four right-handed native English speakers participated in the study.

Procedures: The experiment consisted of two block-design protocols: one for reading and one for writing. The reading protocol consisted of 4 conditions that were used to localize the VWFA: words, consonant letter strings, checkerboards, and fixation. The writing protocol consisted of 5 conditions: written naming of pictures, spoken (subvocal) naming of pictures, copying letter strings, copying scribbles, and fixation. Each functional imaging run consisted of 4 repetitions of the reading or writing conditions listed above. Two runs of reading and writing were administered to each subject, for a total of four runs per subject. For the reading tasks, each block lasted 20 seconds except for the fixation condition (12 sec) and consisted of 13 items per block. Each item was presented for 1000 ms with an interstimulus interval of 500 ms. The same time epochs were used in writing as in reading except that each item was presented for 4 seconds. In the fixation condition, a cross appeared in the center of the screen. For the writing protocol, an iconic instruction appeared at the beginning of every block to indicate whether it was a spoken naming or a writing task.

Stimuli: A total of 130 words of 4-7 letters in length were presented for the reading tasks. The items were divided into 2 sets and were balanced in terms of concreteness, imageability, familiarity, and frequency using the MRC Psycholinguistic Database. One

hundred thirty consonant strings (e.g., trpsf) were generated for the letter string control condition, with equal number of strings of each length from 4 to 7 letters. Fifty picture items were selected for each of the written- and spoken-naming conditions such that the lexical features of the picture names were not significantly different from the words used for the reading task. Alphabetical consonant strings of 4-5 letters were used for copying letter strings. Three types of scribbles (i.e., circular, vertical, and oblique) were used for the scribble-copying control condition. All experimental conditions and stimuli were presented using E-prime.

Image acquisition: Functional images were acquired on a GE 3T whole-body MRI system using a spiral in-out acquisition protocol with the following parameters: matrix= 64 x 64, TR= 2000 ms, TE= 40 ms, FOV= 25 cm, flip angle= 90, number of slices= 26, slice thickness= 5 mm.

Image analysis: Images were reconstructed and then analyzed in SPM2 (http://www.fil.ion.ucl.ac.uk/spm). All images were motion corrected and spatially normalized to the standard MNI (Montreal Neurological Institute) EPI template. Normalized images were resliced to 2 x 2 x 2 mm voxels and smoothed with an isotropic 8 mm FWHM Gaussian kernel.

## Results

The contrasts of interest in reading were the following: words – letter strings, words – checkerboards, words – fixation, letter strings – checkerboards, and letter strings – fixation. The contrasts of interest in writing were the following: written – spoken picture naming, written picture naming – letter strings, written picture naming – scribbles, letter strings – scribbles. For this study, we focused on the written - spoken picture naming comparison because this contrast was intended to isolate the cortical regions specific to the retrieval of orthography in spelling while subtracting out activations attributable to visual analysis of pictures, as well as semantic and phonological processing.

Of the reading tasks, the words – fixation contrast produced the most consistent activation of the VWFA (x = -42, y = -60, z = -12) across subjects (Figure 1a). These coordinates were in close proximity to the coordinates reported for the VWFA by Jobard et al. (2003) based on a meta-analysis of 35 neuroimaging studies (MNI: x = -44, y = -58, z = -15; SD: x = 4, y = 5, z = 6 mm) (Figure 2a). Critically, the same cortical region was also activated in the written-spoken naming contrast in our study (Figure 1b and 1c) and also by Beeson et al. (2003), in an imaging study of spelling that used a written generative naming task (Figure 2b).
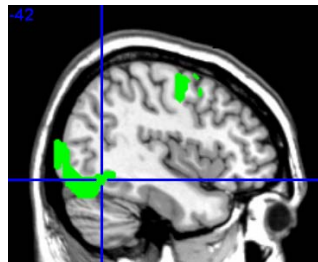
## Conclusion

Our results showed that a left inferior temporo-occipital cortical region corresponding to the VWFA is associated not only with orthographic processing in reading but is also recruited during the retrieval of orthographic information in spelling. These findings are consistent with shared-component cognitive models that postulate a single orthographic lexicon mediating both reading and spelling. Furthermore, the results of this study suggest that the mid-lateral portions of the left fusiform gyrus, not the angular gyrus as originally proposed by Dejerine (1891), play a critical role in orthographic processing. From a methodological perspective, our results confirmed that the novel approach of comparing patterns of cortical activation within the same group of individuals can successfully localize the cortical regions shared between reading and spelling. This technique, therefore, may contribute to the resolution of some long-standing controversies in the neuropsychological literature on alexia and agraphia.
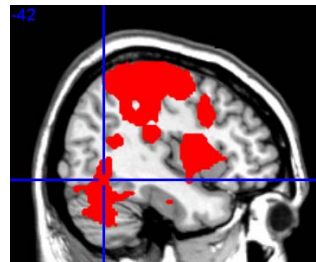
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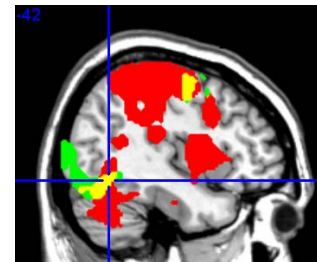
Figure 1. Sagittal sections showing activation on the word – fixation contrast in reading, activation on the written – spoken naming contrast in writing, and the overlapping area of the two contrasts on the same coordinate (x = -42, y = -60, z = -12): (1a) word – fixation in green; (1b) written – spoken naming in red; (1c) overlapping area of (1a) and (1b) in yellow
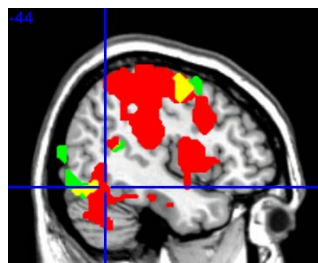


1a.
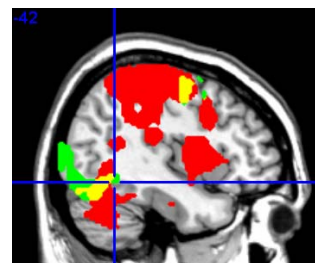words – fixation



1b.
written – spoken naming



1c.
Overlap of word – fixation and written – spoken naming

Figure 2a. The area of overlap of the word – fixation and written – spoken naming contrasts overlaid on the coordinates reported for the visual word form area (VWFA) by Jobard et al. (2003) (x = -44, y = -58, z = -15). (2b) activations common to reading and spelling from the current study overlaid on the coordinates from a study of written generative naming by Beeson et al. (2003) (x = -42, y = -54, z = -12). (word – fixation in green, written – spoken naming in red, overlapping area in yellow )



2a.
Crosshairs to indicate centerpoint for the VWFA from Jobard et al. (2003) relative to current study.



2b.
Crosshairs to indicate centerpoint from Beeson et al. (2003) relative to current study.