Published in final edited form as:
Neuroimage. 2017 February 15; 147: 554–567. doi:10.1016/j.neuroimage.2016.12.054.

Shared Orthographic Neuronal Representations for Spelling and Reading

Jeremy J. Purcell[1], **Xiong Jiang**[2], and **Guinevere F. Eden**[1]

[1]Center for the Study of Learning, Department of Pediatrics, Georgetown University Medical Center

[2]Department of Neuroscience, Georgetown University Medical Center

Abstract

A central question in the study of the neural basis of written language is whether reading and spelling utilize shared orthographic representations. While recent studies employing fMRI to test this question report that the left inferior frontal gyrus (IFG) and ventral occipitotemporal cortex (vOTC) are active during both spelling and reading in the same subjects (Purcell et al., 2011a; Rapp and Lipka, 2011), the spatial resolution of fMRI limits the interpretation of these findings. Specifically, it is unknown if the neurons which encode orthography for reading are also involved in spelling of the same words. Here we address this question by employing an event-related functional magnetic resonance imaging-adaptation (fMRI-A) paradigm designed to examine shared orthographic representations across spelling and reading. First, we identified areas that independently showed adaptation to reading, and adaptation to spelling. Then we identified spatial convergence for these two separate maps via a conjunction analysis. Consistent with previous studies (Purcell et al., 2011a; Rapp and Lipka, 2011), this analysis revealed the left dorsal IFG, vOTC and supplementary motor area. To further validate these observations, we then interrogated these regions using an *across-task* adaptation technique, and found adaptation across reading and spelling in the left dorsal IFG (BA 44/9). Our final analysis focused specifically on the Visual Word Form Area (VWFA) in the vOTC, whose variability in location among subjects requires the use of subject-specific identification mechanisms (Glezer and Riesenhuber, 2013). Using a functional localizer for reading, we defined the VWFA in each subject, and found adaptation effects for both *within* the spelling and reading conditions, respectively, as well as *across* spelling and reading. Because none of these effects were observed during a phonological/semantic control condition, we conclude that the left dorsal IFG and VWFA are involved in accessing the same orthography-specific representations for spelling *and* reading.

Corresponding author: Guinevere F. Eden, D.Phil., Center for the Study of Learning, Georgetown University Medical Center, BOX 571406, Suite 150, Building D, 4000 Reservoir Road, NW, Washington, DC 20057, T: 202-687-6893, F: 202-784-2414, edeng@georgetown.edu.

Keywords

reading; spelling; typing; FMRI; inferior frontal gyrus; IFG; visual word form area; VWFA

Introduction

Written language is a promethean cultural invention that has allowed humans to express thoughts and communicate throughout the millennia. In modern society, reading text and writing out ideas are critically useful skills that require years of education. Naturally there are inherent differences between those cognitive and sensorimotor skills required to read words and those used to write them. Whereas reading involves the visual perception of letter strings which are mapped onto orthographic, phonological and semantic components for oral production, writing involves the translation of these concepts from orthographic representation to sequential motor commands used to generate word-specific letter sequences (Caramazza and Miceli, 1990; Ellis and Young, 1988; Rapcsak and Beeson, 2002; Rapp and Hillis, 2002; Roeltgen and Heilman, 1985). There is general agreement that semantics and phonology are not unique to either reading or spelling as they form the core cognitive functions in the spoken language system. Although it is also clear that fluent reading and spelling depend on accessing orthographic representations (i.e. the memories of the sequences of letters that comprise a word), it is not known whether these are the *same* exact orthographic representations or whether reading and spelling call upon *different* orthographic representations.

The question of independent versus shared orthographic systems for spelling and reading originated from the neuropsychology literature. Support for the independent orthography model stems from work which demonstrated that there can be damage that impairs spelling but not reading (Beauvois and Dérouesné, 1981; Roeltgen and Heilman, 1984), as well as damage that impairs reading but not spelling (e.g. Cumming et al., 1970; Friedman, 1982). Such work led to the theory that there are distinct orthographic long-term memory components for spelling and reading (Patterson and Shewell, 1987). While this suggests that there is some segregation of cognitive functions, there is also a significant body of evidence instead suggesting that there are shared components for orthographic processing. Specifically, there are numerous reports of brain damaged individuals with a deficit in both spelling and reading (Behrmann and Bub, 1992; Philipose et al., 2007; Rapcsak et al., 2007; Tsapkini and Rapp, 2010). In particular, the work of Behrmann and Bub (1992) described an individual with impairments in spelling and reading for the same irregular words (i.e. words with a low phoneme to grapheme probability, e.g. *yacht*), which suggests a shared orthographic long-term memory store. Furthermore, there has been a report of a treatment generalization effect in an individual with acquired dyslexia, such that there was improved performance in spelling for those words that were trained with reading (Hillis, 1993). This speaks in support of the idea that spelling and reading can access shared orthographic long-term memory representations.

Behavioral studies of spelling and reading in healthy participants also support the theory that there are shared orthographic representations used for both spelling and reading. For instance, it has been reported that, compared to words that are correctly spelled, words that are incorrectly spelled (i.e. that have low-integrity orthographic long-term memory representations) are less accurately identified during a reading lexical decision task (Burt and Tate, 2002). Furthermore, it was found that literate adults were poor at visually distinguishing misspelled words from actual words only for the words that they themselves were poor at spelling and not for words that they were good at spelling (Holmes and Carruthers, 1998). Finally, in a repetition priming study, it was found that spelling a given word primed performance on a reading task for that same word, but not for different words (Monsell and Coltheart, 1987). A parsimonious interpretation of the behavioral findings is that orthographic long-term memory representations for spelling and reading are shared.

Although the aforementioned findings predominantly support shared orthographic components for spelling and reading – in particular, orthographic long-term memories – evidence from cognitive behavioral experiments alone cannot adjudicate whether there are shared orthographic representations at the *neural* level in normal literate adults. Such a proposal requires direct investigation of the neural underpinnings of spelling and reading.

Brain imaging studies have begun to shed light on this matter, with most focused on reading and few on spelling. Considering neuroimaging studies of reading first, several meta-analyses have been conducted, providing a useful way of assimilating the most salient results. For example, the most recent of these meta-analyses was conducted in children and adults; this work reports that neuroimaging studies in adults using a variety of reading tasks show converging brain activation in the following regions: left ventral occipitotemporal cortex (vOTC), left inferior frontal cortices, left parietal cortices, bilateral supplementary motor areas, and right cerebellum (Martin et al., 2015). The left vOTC, parietal and inferior frontal cortices are considered the canonical brain areas involved in reading, and will be considered in more detail here.

The left parietal cortex has been associated with reading and phonological processing and has been deemed critical for early reading development (Pugh et al., 2001). Specifically, the supramarginal and posterior superior temporal gyri have been identified in fMRI studies of pseudoword reading and phonological manipulation and are therefore thought to support the grapheme-phoneme conversion processes necessary for reading (e.g., Jobard et al., 2003; Simos et al., 2002). The posterior parietal cortices on the other hand have been associated with attentional processes. Generally, the left posterior parietal is thought to form a fronto-parietal network with the SMA thus forming an attentional control network involved in goal-directed cognitive functions (Corbetta et al., 2008; Spreng et al., 2010); it has recently been proposed that these regions form a fronto-parietal attentional network for reading (Martin et al., 2015).

The left IFG, on the other hand, is often associated with a more diverse set of functions during reading, including phonological, semantic, and orthographic processing. With regards to phonology, it is associated with articulatory planning required for overt reading, consistent with the classical notion of Broca’s area in spoken production (Guenther, 2006; Price, 2012; Taylor et al., 2013). Furthermore, it is associated with aspects of both lexical and sublexical processing; specifically, it is involved in the selection of the correct phonological lexical representations among competing alternatives (e.g., Heim et al., 2013; Righi et al., 2010), and the sublexical mapping of individual graphemes to their corresponding phonemes (Fiez et al., 1999; Jobard et al., 2003; Poldrack et al., 1999). In the semantic domain it is associated with accessing semantic representations during reading (Binder et al., 2009; Binder and Desai, 2011; Poldrack et al., 1999), and specifically the selection of the correct semantic representations among competitors (Thompson-Schill et al., 1997). The left IFG is also involved in orthographic processing. For instance, in studies of reading, the left IFG has been shown to be sensitive to the written frequency of letter combinations (e.g. infrequent letters and common bigrams) (Vinckier et al., 2007), as well as the frequency of whole written words (Fiez et al., 1999; Kronbichler et al., 2004).

The visual word form area (VWFA) in left vOTC has gained prominence in the neuroimaging literature as being consistently and selectively activated during whole word reading (Baker et al., 2007; Cohen and Dehaene, 2004; Gaillard et al., 2006; McCandliss et al., 2003). Although the specific function of this area has been debated in recent years, the VWFA is generally thought to participate in processing learned orthographic long-term memory representations, either as one component of an extended network or as a regionally focal area that hosts neurons which process orthographic long-term-memory representations (e.g., Dehaene and Cohen, 2011; Price and Devlin, 2011). Specifically, it has been found that the VWFA is active in literate, but not illiterate adults (Dehaene et al., 2010), providing evidence that it becomes entrained to orthographic features through the process of learning to read. Further, it is functionally selective to reading words while being invariant to other features such as case, font or size (Dehaene et al., 2001; however see Wimmer et al., 2016). It has also been found that the VWFA contains neuronal populations that are selectively tuned to whole visual word representations (Glezer et al., 2009; Schurz et al., 2010), thus providing support for the idea that this site is associated with orthographic lexical input processes for reading. Together, this work fits well with the lesion studies that have identified the left vOTC as being selectively required for normal reading (Cumming et al., 1970; Gaillard et al., 2006; Sheldon et al., 2008).

Turning to spelling, a relatively smaller corpus of neuroimaging studies reveals a consistent left lateralized set of regions associated with spelling (Planton et al., 2013; Purcell et al., 2011b). One recent meta-analysis of brain areas involved in spelling (Purcell et al., 2011b) found high likelihood of activation for the central components of spelling in the left vOTC, superior temporal gyrus, intraparietal sulcus, and IFG. Of particular interest is the left IFG and vOTC, both of which have been shown to contribute to intact orthographic long-term memory processing in spelling. For instance, fMRI activation while spelling has been found to be modulated by word frequency (i.e. differences in spelling high frequency words relative to infrequently occurring words) (Rapp and Dufor, 2011; Rapp and Lipka, 2011), and by lexicality (i.e. differences in spelling real words relative to pseudowords, e.g. fodap) (DeMarco et al., 2017; Ludersdorfer et al., 2015). The modulation of neural activity due to frequency and lexicality are indicative of orthographic long-term memory because orthographic representations underlying higher frequency words are considered to be better inculcated into the orthographic long-term memory stores as compared to either low frequency words or pseudowords. This neuroimaging work is consistent with lesion literature which finds that individuals with damage to either the left IFG or the left vOTC have impaired access to orthographic long-term memories for spelling (Rapp et al., 2015).

While earlier brain-based studies of reading and spelling occurred independently of each other, more recent work has attempted to examine the neural substrates associated with *both* tasks within the *same* individuals. Neuroimaging studies have demonstrated that both spelling and reading-related tasks activate the left IFG and the left vOTC within the same group of participants (Purcell et al., 2011a; Rapp and Dufor, 2011; Rapp and Lipka, 2011). These studies suggest that both these areas contain neurons that are called upon for reading and neurons that are called upon for spelling. However, it is unknown whether the same sets of neurons within these areas are active for spelling and reading or if they are different neurons residing in close proximity; both possibilities could lead to concomitant reading and spelling deficits in lesion patients or result in spatial overlap of brain activity. In other words, neuronal populations that encode orthography for reading and separate neuronal populations that encode orthography for spelling, *could* be intermixed within the same region without actually engaging in the exact same task. Therefore, cortical co-localization of brain activity using brain imaging is not sufficient to determine shared versus independent orthographic representations across spelling and reading.

Ultimately, it is the limited spatial resolution of fMRI that prohibits direct examination of shared versus unique neuronal responses associated with different representations or processes. This limitation in spatial resolution is due to, for the most part, the Blood Oxygenation Level Dependent (BOLD) response being an indirect measure of local neuronal responses (Logothetis et al., 2001). In recent years, attempts to circumvent this limitation have been employed by methods such as fMRI-Adaptation (fMRI-A) or Multivariate Pattern Analysis (MVPA). In MVPA the collective response pattern across a set of voxels is examined; if two conditions share a stimulus feature, they are predicted to have a relatively more similar multi-voxel response pattern (Mahmoudi et al., 2012). In fMRI-A the combined neural response within a set of voxels is examined under two conditions. If these share a stimulus feature, they demonstrate a relatively suppressed neuronal response and hence lower brain activity (Grill-Spector and Malach, 2001). This suppressed (or adapted) neuronal response is due to stimulus repetition and was initially observed in single-unit recordings in monkey inferior temporal cortex (Desimone, 1996). The same phenomenon has been effectively used in human fMRI-A to characterize functional properties of neural populations by varying the commonality of stimulus attributes between conditions and using the relative neuronal responses to gauge whether neuronal populations are selective to a common stimulus attribute (Grill-Spector, 2006; Grill-Spector et al., 2006; Grill-Spector and Malach, 2001; Henson and Rugg, 2003; Kourtzi and Kanwisher, 2001). Whereas, MVPA effects can be driven not only by the same sets of neurons but also by neuronal responses to different clusters of neurons within the same set of voxels (Epstein and Morgan, 2012; Hatfield et al., 2016), it is believed that the fMRI-A effects are driven primarily by adapted responses in the same sets of neurons (Drucker & Aquirre 2009). Importantly for the purpose of the current study, fMRI-A has proven very useful in studies on the specialization of brain areas involved in word processing. For example, it has been used by Dehaene et al., (2001) to demonstrate that orthographic neural representations in the left Visual Word Form Area (VWFA) are invariant to the case of the written word, and by Glezer et al., (2015,

2009) to demonstrate that there are whole orthographic lexical units represented in the left VWFA.

Here, we used fMRI-A to identify areas in the brain that demonstrate shared orthographic representations for spelling and reading. The logic of our approach is that when a common stimulus feature (e.g. orthography) is presented more than once in different conditions (e.g. spelling and reading), there will be a lower response in neurons where a common stimulus feature is processed (Grill-Spector, 2006; Grill-Spector et al., 2006; Grill-Spector and Malach, 2001; Henson and Rugg, 2003; Kourtzi and Kanwisher, 2001). Specifically, reading a particular word involves neuronal responses associated with reading that word; and when that word is subsequently read again (as the second stimulus), one would expect adaptation in the response. Similarly, when the first stimulus requires the reading of a particular word followed by the spelling of that same word, one would expect adaptation across the two tasks in those regions where neurons code for representations or processes used to both read and spell that particular word. It is both of these types of adaptation (within and across adaptation) that are implemented in the current study. However, this demonstration alone would not be sufficient to determine the exact nature of the processes shared by reading and spelling, because phonological or semantic aspects subserving both reading and spelling could also be at play. In order to ensure that these representations are specific to orthography, another task is required that also involves phonology and semantics, but not orthography. For this, we used speaking a word, followed by reading that word. Specifically, we sought evidence for adaptation effects *across* spelling and reading, without an analogous adaptation effect for speaking and reading. Together such use of fMRI-A can serve to identify specific joint representations for orthography for spelling and reading.

We first examined adaptation effects separately for spelling and for reading. Then, we examined the convergence of these two adaptation effects via a conjunction analysis as a way to build on prior work employing traditional fMRI methods to examine the spatial co-localization for reading and spelling (Purcell et al., 2011a). Next, we used fMRI-A to identify brain regions that show adaptation effects *across* spelling and reading in these same brain areas. Finally, we examined the VWFA using an approach that was subject-specific, given the between-subject variability of its location (Glezer and Riesenhuber, 2013). For all of these aspects of the study we included a control experiment (repetition of heard words) to allow us to account for and rule out other processes shared by these tasks (phonology or semantics). Together this served the goal to determine if there are neuronal process underlying *orthographic specific* processing during reading and spelling.

Methods

Participants

Sixteen (6 male and 10 female) right-handed, healthy adults (Mean age = 23.2; Range = 18–27 years) participated in this study and in the study reported in Purcell et al., (2011a). Handedness was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were monolingual English speakers with no history of neurological disorders or learning disabilities. Standardized neuropsychological tests for reading and spelling (Woodcock et al., 2001) were administered in order to ensure good reading and spelling skills (i.e. standard score >85 on either test). Participants were required to have normal or corrected-to-normal vision, and be able to type on an American QWERTY keyboard at a 50 word per minute (WPM) rate without looking at their hands. This minimum WPM rate was assessed using a standard typing test program (MaxTypeLITE, 2006). All participants were recruited from the student population at Georgetown University. Experimental procedures were approved by Georgetown University's Institutional Review Board and written informed consent was obtained from all subjects prior to the study.

Design of Event-Related fMRI-Adaptation Study

We conducted an fMRI-A study for spelling and reading, designed to test our hypothesis in two complementary ways: (1) We separately identified (a) areas that show adaptation to spelling of the same words and (b) areas that show adaptation for reading of the same words, and then (c) examined co-localization of the two. For this, the experiment contained separate trials for reading and spelling, allowing examination of adaptation effects *within* spelling and reading, separately, and then to test for their co-localization via a conjunction analysis. (2) We examined orthography-specific adaptation effects *across* spelling and reading to identify localized populations of neurons that code for orthographic representations shared when either spelling or reading the same word. For this, the experiment contained pairings of spelling and reading trials that allowed for the examination of adaptation effects *across* spelling and reading (e.g. same words were read then spelled).

In order to determine if these across spelling and reading adaptation effects were orthography-specific we conducted a parallel control experiment that involved repeating and reading (see below). For this control experiment we did not expect to see adaptation *across* repeating and reading words, thereby demonstrating that the across spelling and reading adaptation effects are specific to shared *orthographic* processing as opposed to shared phonological or semantic processes.

As presented in Figure 1A, the study consisted of a series of experiments with spelling and reading trials. During "Spell" trials an auditory word was presented within a duration of 750ms after which participants spelled the word by typing it on the MRI compatible keyboard (Mag Design and Engineering). Critically, the Spell task was performed *without* visual feedback. During "Read" trials, participants covertly read a visual word that was presented for 500ms. In addition, participants were instructed to perform an odd-ball semantic task on both the Spell and Read trials: if the stimulus was of the semantic category "body part" (e.g. hand), subjects were required to press the space bar after typing the word (for Spell trials) or after viewing the word (for Read trials). Targets were present on 16% of the trials. This task ensured that subjects processed the meaning of each word regardless of trial type (i.e. Read or Spell). All target trials were excluded from the fMRI data analysis because their response is not equivalent to that for non-target trials (e.g., Dehaene et al., 2001). When not typing, subjects were instructed to keep their fingers on the "home keys" (i.e. ASDFJKL;) which were identifiable to the touch by small rough tabs added to the keyboard. Half of the visual stimuli were presented in capital letters and the other half in lower case, to ensure that any observed adaptation effects are specific to *abstract* orthography representations and not to low-level visual features of the word (Cohen et al., 2002). Trials were separated by a jittered time interval of 5, 7, or 9 seconds; interval frequency was counterbalanced across all conditions.

In order to allow for regular rest breaks during the fMRI scan session the study was broken up into four separate consecutive runs with short in-scanner intervals between each run. Within each run, trials of interest were ordered with the following constraints: (1) half used the same word as presented in the previous trial and half used a different word; (2) half involved spelling and half involved reading; (3) half were followed by a trial of the same type (e.g. Spell followed by a Spell trial) and the other half were followed by a trial of a different type (e.g. Spell followed by a Read trial). Trials were sorted into 8 conditions based on the previous trial as summarized in Figure 1B. From here onwards, conditions will be labeled with an upper and lower case word separated by a hyphen (e.g. spell-READ), where the upper case word refers to the current trial, the lower case word refers to the just-previous trial. For example, a trial that involves reading, but is preceded by a spelling trial of the same word will be referred to as “spell-READ Same” trial. Adaptation effects were derived from the current trial based on the just previous trial for all conditions. A continuous carry-over fMRI-A design was employed which dictates that each trial type follows every other trial type an equal number of times (i.e. probability of the next condition is equated across conditions) (Strange et al., 2000). This counterbalance scheme was developed in MATLAB (The Mathworks, MA). For each run there were 72 trials of interest, 15 (not analyzed) semantic target trials and 8 (not analyzed) non-target trials which follow a target trial. Across all 4 runs, this produced 36 trials per condition.

It is important to note that only the spell-READ condition trials were used to examine adaptation effects between spelling and reading. It is only for these trials that the participant spells the word without having just read that word within the context of the experiment (i.e. followed by a reading trial). Therefore, for the spell-READ trials the retrieval of the correct spelling of a word from orthographic long-term memory requires the retrieval of memories encoded prior to the scan session. This is not the case for the read-SPELL condition trials; for these trials the words were just read a few seconds prior. Therefore, these trials may involve other cognitive mechanisms such as the online learning of the correct spelling of a word (e.g. for a word the participant did not know how to spell correctly prior to viewing it during the experiment), and this may impact the adaptation effect for these trials; for instance learning during fMRI-adaptation experiments has actually been associated with repetition enhancement instead of suppression (Segaert et al., 2013). Therefore, in order to avoid issues regarding the equivalency of the spell-READ to that of the read-SPELL trials, the read-SPELL trials were included in the study for the purpose of counterbalancing only, and were not used in the analysis (i.e. as an *a priori* design decision preceding data acquisition).

To control for more general effects of semantics or phonology, we included a Repeat/Read fMRI-A experiment using the same design as the other experiments in the study. From the participants’ perspective, however, it only differed in that instead of spelling auditory words, subjects were instructed to repeat the word (quietly and with minimum head movement). Subjects were also instructed to place their fingers on the space bar and only use it to respond to the semantic “body part” category trials. Results from this experiment were used to test for the orthographic specificity of our main results.

Stimuli for Event-Related fMRI-Adaptation Study

A total of 404 nouns were obtained from the CELEX Lexical Database (Baayen et al., 1993). Words were selected if they occurred at least 1.25 times more often as a noun than as a verb and none were homophones (e.g. bear/bare). This larger list was partitioned into two separate lists of 180 words that were labeled List 1 and 2; each list had an equal number of 4, 5, and 6 letter words. The remaining 44 words belonged to the semantic category “body part” (e.g. brain). Words from List 1 and 2 were matched on word frequency, consistency, syllable number, auditory word duration, and approximate left/right hand use required while typing (see Table 1).

Word frequencies were obtained from the MCWord Orthographic Database (Medler and Binder, 2005). Consistency measures were calculated from the phoneme-grapheme positional probability mappings reported in Hanna et al., (1966) as follows: the positional probability of a mapping between a given phoneme and grapheme was calculated for each syllable within each word and then averaged within word. Considering that for typing, activation patterns in motor regions can be influenced by the amount of key-presses used by the right or left hand, we calculated the average percentage of key-presses on a QWERTY keyboard required by each hand for each word to ensure they were balanced (e.g. the word ‘camp’ requires 2 key presses for the right hand (“c”, “a”) and 2 key presses for the left hand (“m”, “p”) when typing).

Spoken and visual image files were obtained for each word used in these experiments. Spoken words for the Spell task and the Repeat task were obtained from the Linguistic Data Consortium (1999). Each audio file was processed in MATLAB in order to measure the spoken word duration, standardize the root mean square amplitude, and addend varied periods of silence to the beginning of each audio file in order to ensure each audio file was 750ms in duration. Visual word images for the reading test were developed using MATLAB to eliminate background variations and to standardize image size to approximately 2x4° visual angle. Stimuli were presented using Presentation software (Neurobehavioral Systems, Inc.). ANOVAs were run on frequency, duration, and % right hand usage parameters for each list of words. There was no main effect for frequency, syllable number, duration or hand use across all 3 lists of words.

Single Subject Functional VWFA ROI

In addition to the whole brain analysis in Experiment 1 (described below), which was followed by a region of interest (ROI) analysis in Experiment 2 (see below), we also functionally localized another ROI, the VWFA, this time on an individual (single-subject) basis. This “localizer” was then used as the ROI for focusing the analyses of the fMRI-A data (similar to Experiment 1 and 2) on the subject-specific Visual Word Form Area. Details regarding the experimental design of this localizer experiment are reported in Purcell et al. (2011a). Briefly, for the Reading Localizer we presented 30sec blocks of visual words, checkerboards, or a fixation cross resting condition. For the Word and Checkerboard conditions, 10 visual stimuli were presented for 2250ms, with a 750ms fixation interval between each. Subjects were instructed to attend to all stimuli, but for the Word condition, they were further instructed to covertly read each word.

Stimuli for the Single-Subject Functional VWFA ROI

A lists of 40 items were obtained from the CELEX Lexical Database (Baayen et al., 1993). This list had equal numbers of 3, 4, 5, and 6 letter nouns. None of the stimuli were homophones. None of the words were shared with those presented in the fMRI-Adaptation experiments. The checkerboard active control condition covered 2x4° visual angle, i.e. similar extent as the visual word stimuli. Further details regarding the stimuli used are provided in Purcell et al., (2011a).

Behavioral Data Analysis

Behavioral data obtained from the Spell/Read experiment and Repeat/Read experiment were processed in MATLAB. Accuracy, reaction time, inter-key-interval (IKI) and response duration data were obtained for the Spell trials in the Spell/Read experiment. Accurate trials were defined as those for which subjects produced the correct key-press sequence for a given word as well as those just one position to the right or left of the correct key (to allow for slight finger misplacements). Incorrect Spell trials were excluded from further analysis. Reaction time was measured as the time from the end of the stimulus presentation to the start of the first key-press. IKI was measured as the average difference in response times for adjacent key-presses across all key-presses in a given word. Response duration was measured as the time from the end of the stimulus presentation to the final key-press. We tested for behavioral adaptation effects by performing a within-subject 2x2 repeated-measures ANOVA on the accuracy, reaction time, and IKI data, followed by post-hoc paired t-tests, ($p = 0.05$, two-tailed) comparing the Different and Same trials for the Spell trials (i.e. the spell-SPELL and read-SPELL conditions).

Accurate semantic trials were defined as those for which subjects pressed the space bar when they heard or saw a “body part” word. Accuracy was scrutinized for the Read trials and Spell trials in the Spell/Read experiment and Read and Repeat trials in the Repeat/Read control experiment. Our criteria for exclusion from further analysis was performance below 60% on any given experimental run, however no runs had to be excluded based on these criteria.

MRI Acquisition

Subjects were placed in a comfortable typing position prior to the start of the scanning session: The MRI compatible keyboard was positioned on the participants’ waist and foam padding was placed under their arms. Visual stimuli were projected onto a rear screen with a LCD projector and viewed through an angled mirror. Auditory stimuli were presented binaurally through electrostatic MRI-compatible noise-cancellation headphones (STAX). Head movement was minimized via foam cushions. Participants were asked to fixate on a central cross throughout the experiments.

Four continuous-acquisition functional EPI sequences were used each for the Spell/Read and Repeat/Read fMRI-A experiments. These data were acquired using a 12-channel head coil with the following parameters: flip angle = 90°, TR = 2000ms, TE = 30ms, FOV = 205mm, 64x64 matrix, 37 axial slices (thickness = 3mm, no gap; in-plane resolution = 3.2x3.2mm^2). Each run (four for the Spell/Read and four for the Repeat/Read) had a total of 348 volumes and scan time of 11min, 36sec.

For the Independent Functional VWFA Localizer scan we employed the same parameters as for the Spell/Read and Repeat/Read fMRI-A experiments except that this scan had a total of 192 volumes (60 volumes each for the reading and checkerboard conditions and 72 volumes for the fixation rest condition) and a total scan time of 6min, 24sec.

Finally, also acquired 3D T1-weighted MPRAGE structural images used for spatial co-registration: TR = 1600ms, TE = 4.38ms, FOV = 256, 160 axial slices; effective resolution of 1mm^3.

MRI Data Pre-processing

All pre-processing and statistical analysis of the fMRI data was performed using the software package SPM8. The anatomical MPRAGE was normalized to a standard Montreal Neurological Institute (MNI) reference anatomical template brain (Collins et al. 1998). First, we corrected for head motion by realignment of each scan to the first image, co-registering the functional scans with the MPRAGE anatomical scan, and then slice time correcting the data by phase shifting the data in each slice to the middle slice acquisition. We then normalized all of the data via the same warping parameters used to normalize the MPRAGE scan. The images were then resliced to 2mm^3 and smoothed with an isotropic 6mm Gaussian kernel.

In order to ensure that the fMRI data was not confounded by excessive head motion, runs were excluded if their overall motion in the vector sum of the x, y, and z direction movement was greater than one voxel (3mm) or if more than 25% of the time points had scan-to-scan movement above a pre-designated threshold (0.2mm). Only 1 run was excluded for the Spell/Read experiment.

fMRI-A Statistical Analyses

As described above, we addressed two questions. First, do spelling and reading demonstrate co-localized fMRI adaptation effects? This was addressed by determining if there is a conjunction of adaptation effects for the two separately acquired *within* conditions for spelling and reading. Second, are there orthography-specific adaptation effects *across* spelling and reading within this area? This was addressed by directly looking for an adaptation effect *across* spelling and reading trials in the same run. In addition, these effects were considered in the context of the results from the control experiment where Repeat/Read stimuli were used.

These analyses began at the single-subject level with whole-brain statistical analyses for the Spell/Read experiments and Repeat/Read control experiment. We first performed a temporal filtering with a high pass filter (128sec) on the fMRI signal. Next, we set up a regression model by first convolving a standard hemodynamic response function (HRF) with the trials that corresponded to each condition in the Spell/Read experiment and the Repeat/Read experiment (described in Figure 1B). In order to account for non-stimulus dependent noise variance we included principle component regressors as obtained from the CompCor method which has been shown to account for physiological noise (e.g. respiration and heart rate) without direct measurements (Soltysik et al., 2015). We also added 6 motion parameters (roll, pitch, yaw, x, y, z) into each regression model. In addition, the trial-specific response times (i.e. time to first key-press for the Spell/Read experiment and voice onset time for the Repeat/Read experiment) were included as a regressor of no interest so as to account for variance in the percent signal change driven solely by responding faster or slower to the word stimuli (e.g., Binder et al., 2005; Graves et al., 2009). This was accomplished by assigning the average response time for each trial to the post-stimulus time points associated with the peak BOLD response (4–8sec) within the regression model. We also incorporated an autoregressive (AR1) model to account for serial correlations (Della-Maggiore et al. 2002). Finally, in order to limit the analysis to relevant voxels in the brain, this analysis was constrained by every gray-matter area defined by the standardized Harvard-Oxford atlas distributed by FSL (http://fsl.fmrib.ox.ac.uk/fsl/) and developed at the Harvard Center for Morphometric Analysis.

We then ran a multiple regression analysis for the Spell/Read experiment and the Repeat/Read control experiment in order to estimate the percent signal change contrast map associated with each separate condition. To identify group-level adaptation effects we entered these subject-specific contrast maps (additional smoothing of 6mm) into a group-level random effects analysis (Penny and Holmes 2006). It is important to note that throughout these analyses, adaptation effects were determined by contrasting Different conditions to their Same condition counterparts; for example, in order to identify spelling adaptation effects we determined whether on average the percent signal change for the "spell-SPELL Different" condition was greater than for the "spell-SPELL Same" condition as identified in Figure 1B. Furthermore, for this study we were not interested in all of the conditions from these fMRI-A experiments, and as noted in the outlined portions of Figure 1B/C, we only examined pre-planned conditions in order to address our two specific questions.

Experiment 1: Do spelling and reading demonstrate co-localized fMRI adaptation effects?—First, we examined a conjunction of adaptation effects for spelling and reading in a whole brain analysis. The spelling and the reading Same and Different conditions from the Spell/Read experiment were entered into a 2x2 ANOVA with task (Read, Spell) and sequence (Same, Different) as factors. We then performed a conjunction of adaptation effects for the Within spelling (spell-SPELL) and reading (read-READ) conditions (Friston et al., 2005). Results were initially set with a voxel-wise threshold of 0.001; reported results had an FWE corrected cluster-wise threshold of 0.05.

Experiment 2: Do spelling and reading demonstrate orthography-specific adaptation effects across spelling and reading?—We then asked whether the regions identified in the conjunction analysis above (overlap of adaptation effects found for reading and spelling separately), also demonstrated adaptation effects for the *across* spell-READ condition. Ultimately, these areas would be considered to have demonstrated robust adaptation behavior. The fMRI data used to define the regions (as described above) is independent from the data examined here, so as to avoid circularity. Further, in order to determine if the across spell-READ effects were specific to orthographic processing, we tested whether these adaptation effects were significantly greater as compared to the control repeat-READ condition.

We entered the spell-READ and the repeat-READ Same and Different conditions into a 2x2 ANOVA with task (Read, Spell) and sequence (Same, Different) as factors. We then tested for an interaction effect in order to identify brain areas where there are significantly greater adaptation effects for the across spell-Read condition pair as compared to the repeat-Read condition pair. Results were initially set with a voxel-wise threshold of 0.001; reported results had an FWE corrected cluster-wise threshold of 0.05.

Single Subject Functional VWFA ROI Analysis

Lastly, to test the hypothesis that there are adaptation effects across spelling and reading within the VWFA, we independently defined subject-specific VWFA ROIs. This was done by conducting a whole-brain statistical analysis on the data acquired during the VWFA Localizer in each subject. Preprocessing involved temporal filtering with a high pass filter (128sec) and an AR1 model (Della-Maggiore et al., 2002). We then modeled the hemodynamic response for each condition in the reading experiment (Word, Checkerboard, and Fixation). A principal components analysis (PCA) was used to remove estimates of physiological noise as defined by the CompCor method (as described in Soltysik et al., 2015), and the 6 motion parameters (roll, pitch, yaw, x, y, z) were entered as regressors of no-interest. Then, we performed a whole brain contrast for Read > Fix (uncorrected threshold $p < 0.001$) which was masked inclusively by the Read > Checker contrast (uncorrected $p = 0.05$) in each subject. This map had a cluster-level FWE correction level of $p < 0.05$. As is convention in SPM8, this mask did not constrain the number of voxels in the statistical analysis or provide correction for multiple comparisons, but merely served to constrain the number of voxels that were examined in the final map. The peak foci were located within the left fusiform gyrus (as defined by the Harvard-Oxford atlas) that was closest in distance to the canonical VWFA coordinate location, MNI: −43 −55 −17, as reported in Cohen et al., (2002). This method of localizing the VWFA ROI was adapted from previous studies which utilized VWFA ROIs (e.g., Glezer et al., 2009). Subject-specific VWFA peaks are reported in Table 2. The average peak location (with standard deviation) was MNI: −41 −55 −16 (4 5 4) consistent with previous reports of the location of the VWFA (MNI: −42 −58 −17 as reported by Glezer and Riesenhuber, (2013)). A 3mm sphere was generated around each VWFA peak in order to obtain the subject-specific VWFA ROIs.

Using the SPM5 toolbox MarsBaR (Brett et al., 2002), we extracted the average signal across the set of voxels that comprised each subject-specific VWFA ROI. A Finite Impulse Response (FIR) function analysis was obtained from each ROI in each subject, using unsmoothed, normalized data. From the FIR analysis we obtained BOLD response plots for each condition in the fMRI-A experiments. We performed statistical analyses on the peak

BOLD responses (4–8sec post-stimulus) for each of these conditions of interest. The average peak BOLD response data were first entered into group-level 2x2 ANOVA to examine both spelling and reading adaptation effects within the VWFA and then another group-level 2x2 ANOVA to examine the interaction of adaptation effects across spelling and reading vis-à-vis across repeating and reading adaptation effects. Statistics were analyzed in SPSS (SPSS, Inc., 2009).

Behavioral Results

fMRI-Adaptation Experiment: Semantic Oddball Task Results

Semantic oddball task performance for the Spell/Read Experiment was 86% (Range = 72–97%) and for the Repeat/Read Experiment was 87% (Range = 72–98%). There was no significant difference between performance on the spelling and reading trials in the Spell/Read experiment. Additionally, there were no significant differences between the performances on the repeating and reading trials in the Repeat/Read experiments.

fMRI-Adaptation Experiment: Behavioral Results

For the Spell/Read experiments the mean spelling accuracy was 86% (Range = 62–94%). Trials determined as incorrect were excluded from further analysis; this left approximately 31 trials on average remaining for each of the Spell conditions (Range = 23–34). The mean overall reaction time for correct trials on Spell task was 532ms (SD = 188ms) with an average overall response duration of 1467ms (SD = 331ms). These results indicate that participants could perform the spelling task at relatively high accuracy levels with sufficiently fast response durations to fit within the 2sec TR sampling rate of the event-related fMRI designs.

Accuracy, response time and IKI were assessed specifically for the spell-SPELL condition defined in Figure 1B. A paired t-test revealed that there were spell-SPELL behavioral adaptation effects ($p < 0.0001$) as defined by a significantly shorter response time for the spell-SPELL Same condition versus the spell-SPELL Different condition. This effect was not observed for accuracy or IKI.

For the Repeat experiment the mean accuracy was 93% (Range = 74–100%). There were approximately 34 trials on average remaining for each of the Repeat conditions (Range = 27–36). The mean overall voice onset time for correct trials on the Repeat task was 1102ms (SD = 83ms). These results indicate that participants could perform the repeating task with high accuracy. It should be noted that this particular task was not difficult and any errors are likely due to subject fatigue in the scanner or insufficient loudness of voiced responses by the subject.

As mentioned, the trial-specific reaction times for both the Spell/Read and the Repeat/Read experiments were incorporated into the fMRI multiple regression models. In this manner we can ameliorate the effects of behavior on any fMRI adaptation effects. For instance, although we observed a behavioral adaptation effect for the response time in the spell-SPELL conditions, by incorporating these response times into the model we account for variability that is due solely to responding faster; therefore, any BOLD response adaptation effects are more likely due to underlying neuronal selectivity.

fMRI-A Results

Experiment 1: Do spelling and reading demonstrate co-localized fMRI adaptation effect?

The conjunction analysis of the *within* condition spell-SPELL and the *within* condition read-READ whole brain adaptation effects revealed regions in the left dorsal IFG (BA 44/9), supplementary motor area (SMA BA 6), and mid-inferior temporal gyrus (ITG) (BA 37) (see Table 3 and Figure 2). Specifically, the location of the left dorsal IFG region was at the junction of three structures: the pars opercularis (BA 44), premotor cortex (BA 9), and middle frontal gyrus. The left ITG cluster includes the middle portion of the occipitotemporal sulcus (OTS) region which straddles the boundary between the ITG and fusiform gyrus.

Experiment 2: Do spelling and reading demonstrate orthography-specific adaptation effects across spelling and reading?

Using only those regions identified above (left dorsal IFG, SMA, ITG/OTS), we then sought to confirm that there is an adaptation effect *across* spelling and reading, and that this effect is specific to orthography by not being observed across repeating and reading. The results of this analysis revealed an interaction of adaptation effects within the left dorsal IFG (BA 44/9) at the intersection of the inferior frontal sulcus and precentral sulcus. This single cluster demonstrated significantly higher adaptation for the spell-READ condition pair compared to the repeat-READ condition pair (F [1,60] = 15.64; cluster size of 43 voxels, a peak z-value of 4.12, and peak MNI coordinates of −42 6 30); see Figure 3A. In order to provide a more detailed exploration of these results, an FIR analysis was used to extract the BOLD response for each of the conditions of interest; these results indicate an adaptation effect for the read-READ, spell-SPELL, and spell-READ conditions, but not for the repeat-READ condition (plotted in Figure 3B/C). There was no effect in the SMA or ITG/OTS.

Single-Subject Functional VWFA ROI Results

We examined the adaptation effects in the subject-specific independent VWFA ROI peaks (see Figure 4). The 2x2 ANOVA for task (Spell/Read), modality type (*within*, *across* modality), and sequence (Same, Different) revealed that there was a main effect of sequence (F [1,15] = 47.3, $p < 0.0001$). Planned post-hoc paired t-tests for adaptation effects in each set of Different/Same condition pairs ($\alpha = 0.05$, 2-tailed) revealed a significant adaptation effect for the read-READ ($p < 0.00001$) and spell-SPELL ($p = 0.003$) conditions (Figure 4D).

Finally, when testing for adaptation effects *across* spell-READ (and the *across* repeat-READ conditions), the 2x2 ANOVA for task (Spell, Read) and sequence (Same, Different) resulted in a significant 2-way interaction (F [1,60] = 4.04; $p = 0.048$). Post-hoc paired t-tests revealed that this interaction was driven by a significant adaptation effect for the spell-READ ($p < 0.00001$) condition, but not the repeat-READ condition ($p = 0.59$): see Figure 4E.

Discussion

In this study, we utilized functional magnetic resonance imaging-adaptation to identify areas in the brain that demonstrate shared orthographic representations for spelling and reading. First, we found that there are three left hemisphere regions that are sensitive to *both* spelling and reading as determined by a conjunction of separate spelling and reading adaptation effect analyses: the dorsal inferior frontal gyrus (IFG), the supplementary motor area (SMA), and the mid-inferior temporal gyrus/occipitotemporal sulcus (ITG/OTS). These results confirm previous reports that the left dorsal IFG and vOTC are involved in *both* spelling and reading within the same participants (Purcell et al., 2011a; Rapp and Dufor, 2011; Rapp and Lipka, 2011). Secondly, an adaptation effect *across* spelling and reading was found in the same left dorsal IFG, and further this *across*-adaptation effect was significantly greater than the repeat-READ condition, indicating that it was driven by orthography-specific processes and not general semantic or phonological level processes. Thirdly, we observed this same pattern of *across*-adaptation effects (significant spell-READ adaptation but not repeat-READ adaptation) within the functionally-defined, subject-specific VWFA regions. Together this work demonstrates, for the first time, that both the left IFG and VWFA contain orthographic neuronal representations that are called upon when subjects are engaged in either spelling or reading the same exact word.

Orthographic Processes in the left dorsal IFG

First, we observed that there was a conjunction of the two fMRI-A effects, *within* spelling and *within* reading, in the left dorsal IFG. This indicates that there are selective processing/representations that are called upon for each task. This finding converges with previous work examining the overlap of activation associated with reading and spelling. In fact, the peak identified in our current reading and spelling adaptation study (MNI = −42 6 30) is less than 1 cm Euclidean distance from the peaks identified in two separate studies that examined the overlap of activation for reading and spelling; these dorsal IFG MNI peaks were −44 4 24 in Rapp and Lipka (2011) and −44 −2 28 in Rapp and Dufor (2011) (the peaks from these studies were converted from Talairach to MNI coordinates using the method described in Lacadie et al., (2008)). This close proximity reinforces these earlier findings by determining that there is not only a conjunction of reading and spelling fMRI activation but also fMRI adaptation in the left dorsal IFG.

However, the limitation in this conjunction analysis, as in prior work, is that this does not speak to whether these *exact* processes/representations are shared, or whether they have separate representations that reside in close proximity to one another in the cortex. Therefore, this region was then probed further and revealed a clear adaptation effect *across* spelling and reading. This demonstrates the presence of neurons sensitive to shared representation/processing for both spelling and reading. Critically, this shared representation/processing was found to be specific to orthographic features of the spelled/read words because there was no adaptation effect *across* spoken production and reading processing within this region.

Much work has indicated that the left dorsal IFG is important for phonological and semantic processing in reading (Fiez et al., 1999; e.g., Fiez and Petersen, 1998; Poldrack et al., 1999;

Pugh et al., 2001). Our findings add to a growing literature to suggest that a portion of the left IFG is specific to orthographic processing. One possible orthographic cognitive component may be in the mapping between specific sublexical orthographic and phonological representations, as has been suggested in reading (Jobard et al., 2003). In the context of the current study, this component would involve the reciprocal mapping system between grapheme-to-phoneme and phoneme-to-grapheme.

Another possibility is that the left IFG is associated with coding long-term memories of orthography. It is generally agreed that an orthographic long-term memory storage is experience dependent, and therefore regions that play a role in orthographic long-term memory would demonstrate activity levels that are sensitive to the frequency of written words and letter combinations. Evidence for such frequency-dependent modulations of activation has been reported by Vinckier and colleagues. Their fMRI study of reading identified a spatial gradient in the left IFG associated with the frequency of letter combinations, such that the more medial IFG was associated with frequent words, and more lateral IFG was associated with bigrams and infrequent letter combinations (Vinckier et al., 2007). Additionally, studies have found that the left IFG is sensitive to the frequency of written words in both reading (Bokde et al., 2001; Kronbichler et al., 2004) and in spelling (Rapp and Dufor, 2011). Furthermore, it has been demonstrated that lesions to the IFG can lead to impairments in orthographic long-term memory processing for spelling (Hillis et al., 2004; Rapp et al., 2015). Taken together, this work suggests that there are neurons in the left IFG that are sensitive to the structure of orthography (e.g. frequency of occurrence of letter combinations and words), and that damage to the left IFG can lead to impairment in the retrieval of orthographic long-term memories for spelling.

Finally, an additional complimentary possible interpretation is that the left inferior frontal gyrus serves generally to coordinate orthographic and phonological representations found in more posterior brain areas during reading and spelling (Bitan et al., 2005; Booth et al., 2002; Mesulam, 1998). A specific proposed function is that it is involved in selecting among competing orthographic units. This is supported by work which has labeled this region the inferior frontal junction (IFJ) - due to its location at the junction of the dorsal pars opercularis, premotor cortex, and middle frontal gyrus - and found that it is associated with cognitive control (Brass et al., 2005; Derrfuss et al., 2005). In particular, the IFJ has been associated with resolving competition during the selection of multiple items (Zhang et al., 2004). With regards to orthography-specific processes, it is possible that the left IFJ serves to accommodate selection demands imposed by tasks that involve activation of competing orthographic representations that are expressed in posterior areas such as the left vOTC. For reading and spelling there may be shared selection demands associated with mapping between the correct orthographic units and phonological/semantic representations. This interpretation is conceptually similar to other studies which suggest that a portion of the left dorsal IFG is associated with selecting among competing lexical units during spoken tasks (Schnur et al., 2009; Thompson-Schill et al., 1998).

A Shared Orthography in the Left VOT cortex

Our second main finding is that a portion of the left vOTC demonstrated fMRI-adaptation effects *within* both spelling and reading as measured with a conjunction analysis. This finding converges with previous fMRI studies of reading and spelling (Rapp and Dufor, 2011; Rapp and Lipka, 2011); for instance the left vOTC peak identified in our current study (MNI = −48 −62 −16) is less than 1 cm from the left vOTC MNI peak (−46 −53 −14) identified in Rapp and Dufor (2011) (this peak was converted from Talairach to MNI coordinates using the method described in Lacadie et al., (2008)). This close proximity reinforces this earlier work by demonstrating that the left vOTC is not only associated with a conjunction of reading and spelling fMRI activation, but also a conjunction of reading and spelling fMRI adaptation.

Furthermore, within subject-specific, functionally-defined VWFA ROIs it was demonstrated that there are adaptation effects *across* spelling and reading. Again, as in the dorsal IFG, these effects were found to be specific to orthography as there was no observed across-adaptation effects for spoken production and reading within this region. These orthography-selective *across* spelling and reading adaptation effects were only detected when using a subject-specific ROI approach, and not in the group analysis within the area identified by the conjunction. This is in line with previous work indicating that selectivity to orthographic specific representations may not be observed at the group level in the VWFA, and that individually-defined VWFA localizers are better suited for probing the function of this region with subtle measures of highly selective effects considering its location and size is variable across subjects (Glezer and Riesenhuber et al., 2013). It should be noted that although the VWFA ROI’s were selected via an independent single-subject localizer, their mean location for the group (−41 −55 −16) was less than 1cm Euclidean distance from the peak conjunction results (−48 −62 −16) reported for *Experiment 1* (Table 3). This suggests that these *VWFA ROI Analysis Results* and the results from *Experiment 1* likely reflect effects from a proximate cortical region. Combined, these findings indicate that the VWFA contains populations of neurons that demonstrate shared orthographic processing for both spelling and reading.

To date, the vast majority of work focused on the VWFA has characterized its role in reading visual words (Baker et al., 2007; Cohen and Dehaene, 2004; Dehaene et al., 2005; Dehaene and Cohen, 2011; McCandliss et al., 2003). This body of work indicates that the VWFA is a functionally-defined region that only develops through the acquisition of literacy skills. Deheane and colleagues have shown that whereas literate adults have a VWFA even if they acquired literacy skills in adulthood, illiterate adults do not have a discernable VWFA (Dehaene et al., 2010). Importantly, this area is associated with orthography-specific representations (Baker et al., 2007), and these representations are invariant to font, size, and visual location in literate adults (Dehaene et al., 2001; however see, Wimmer et al., 2016). Our current findings extend these studies into reading, by demonstrating via adaptation that these orthographic representations are accessed for spelling, as well.

In line with our results that the VWFA is called upon for both reading and spelling is the observation that the VWFA is not only associated with visual-based orthographic representations, but also with somatosensory-based orthographic representations (Buchel et al., 1998; Reich et al., 2011). Of particular note is the work in blind participants, for whom there is a functionally defined area that is selective to brail reading in the same location as where the VWFA resides in sighted participants (Reich et al., 2011). After training congenitally blind adults to read via soundscapes (sounds with unique frequency and temporal modulations specific to different visual objects such as faces, houses, and letters), this same area demonstrated selectivity to soundscape letters and words (Striem-Amit et al., 2012). These results indicate that this area is not purely *visual* in nature, but, at least in part, is associated with orthographic representations abstracted from the visual input modality.

With regards to the specific function of these representations, one possibility is that they are neural instantiations of orthographic long-term memories, and thereby a neural store of orthographic lexical units. This is supported by the lesion literature in that the left vOTC has been observed to be critical site of orthographic long-term memory processing for reading and for spelling (Behrmann and Bub, 1992; Rapp et al., 2015; Tsapkini and Rapp, 2010). In particular, the work of Tsapkini and Rapp (2010) reported on an individual with a lesion that included left fusiform gyrus who demonstrated selective impairments in both reading and spelling, particularly of low frequency and irregular words – hallmarks of a deficit to orthographic long-term memory. Furthermore, the left vOTC in particular has been identified in studies examining the neural sensitivity to measures of long-term-memory processes for orthography as demonstrated by sensitivity to written word frequencies (i.e. high versus low frequency words) and also lexicality (i.e. real word versus nonwords) for both spelling (DeMarco et al., 2017; Ludersdorfer et al., 2015; Rapp and Dufor, 2011; Rapp and Lipka, 2011) and for reading (Glezer et al., 2009; Kronbichler et al., 2004; Mechelli et al., 2003; Schurz et al., 2010). Together this research provides converging evidence that the role of the left vOTC in reading and spelling involves the storage and retrieval of orthographic long-term memory representations (Behrmann and Bub, 1992; Rapp et al., 2015; Tsapkini and Rapp, 2010).

Another possibility is that the VWFA is associated with processing both orthographic lexical units and sublexical orthographic representations during spelling and reading. This idea originates from behavioral literature which report that lexical and sublexical processes operate in parallel during both spelling (Rapp et al., 2002; Tainturier et al., 2013) and reading (Marcolini et al., 2009). In the neuroimaging literature, the left vOTC is consistently more active for pseudowords relative to words in both reading (e.g., Mechelli et al., 2003; Schurz et al., 2010) and spelling (DeMarco et al., 2017); it has been proposed that this higher relative neural response to pseudowords could be due to an online integrative mechanism of sublexical with orthographic lexical units within the left vOTC (DeMarco et al., 2017). Further research is required to parse out the relative role of orthographic lexical and/or sublexical orthographic processing in the left vOTC.

Despite the extensive literature surrounding orthographic processing in the left vOTC, there is still controversy surrounding whether the left vOTC, specifically the VWFA, contains populations of neurons that are specifically tuned to process orthographic representations (Price and Devlin, 2011, 2004, 2003). Neural representations localized to the left vOTC may not be selective to orthography *per se*, but instead these neuronal representations may be distributed across top-down and bottom-up interactions which link visual processing in the vOTC to other language-related processing (Price and Devlin, 2011, 2004, 2003). A major argument for this position is that it has been shown to be responsive to many other types of tasks involving lexical processing such as object naming, repetition, and the aforementioned Braille reading (Buchel et al., 1998; Buckner et al., 2000; Démonet et al., 1994; Giraud and Price, 2001; Thompson-Schill et al., 1999). Our work does not conflict with this argument in the sense that our data makes no claim that the left VWFA *solely* processes orthographic information, only that it demonstrably contains neurons that are selective to orthography and that those are accessed for both reading and spelling. It is entirely possible that this area is involved in multiple functions involving lexical input and output processes; for instance, one study found that although the VWFA is necessary for processing orthographic sequences for written word, it also is involved in lexical output processing (oral reading, naming, and writing) which links input and output representations (Hillis et al., 2005). Our findings support the notion that, along with its other processing roles, the left VWFA may be particularly well suited for interfacing between orthography specific representations and other language representations.

Implications

Beyond the implications of this work to the theory that there are shared orthographic representations for spelling and reading in healthy adults, these results are of potential interest when considering the development of literacy skills in childhood. For instance, reading and spelling skills in normal development have been described to be highly interrelated (Ehri, 1997; Moats, 1995; Perfetti, 1997). Furthermore, in early childhood the reading disability developmental dyslexia is not only associated with impaired accurate and/or fluent word recognition, but also tends to be associated with poor spelling (Lyon et al., 2003). Moreover, not only has the severity of reading impairment in children with dyslexia been found to be correlated with the severity of spelling impairment (Kudo et al., 2015), but children with dyslexia are worse at reading those words that they cannot spell correctly compared to words that they can spell correctly (Angelelli et al., 2011). This appears to be the case when examining different kinds of reading disabilities. For instance, most children with developmental dyslexia have an impairment in phonemic awareness, which leads to difficulties in grapheme-to-phoneme-mapping and decoding of novel words, and this phonemic awareness ability has been found to be associated with spelling ability (Bruck and Treiman, 1990). Furthermore, children with an impairment in reading words that have atypical phoneme-to-grapheme correspondences (e.g. yacht) - referred to as developmental surface dyslexia - tend to have the same type of spelling impairments in reading as they do in spelling (Curtin et al., 2001).

With respect to the neural substrates of learning to read a prominent developmental model posits that phonemic awareness is subserved by temporo-parietal cortex (TPC) and that beginning readers initially use TPC to decode novel words, with an increasing use of vOTC for sight word recognition as they advance and gain familiarity with more frequently encountered words (Pugh et al., 2000). It has been demonstrated that both children and adults with dyslexia have underdeveloped TPC, and this underdevelopment has been tied to their phonemic awareness difficulties (for review see Eden et al., 2016). However, they also have underactive vOTC (Olulade et al., 2015; van der Mark et al., 2009), which might be linked to the role of orthographic processing in reading acquisition (Badian, 1994). It is currently debated whether this vOTC underactivity is a secondary effect of the TPC impairment in dyslexia (i.e. poor grapheme-phoneme-mapping delaying the transition to a more automatic word recognition for commonly encountered words; Pugh et al., 2000) or an independent contributor (Richlan, 2012). Future studies could employ brain imaging to shed light on the mechanism by which spelling intervention helps to improve reading (Santoro et al., 2006), i.e. whether it occurs by virtue of both spelling and reading sharing these representations or in other ways.

Summary

In sum, this is the first study to provide direct evidence in healthy literate adults that there are neural representations of orthography within the left dorsal IFG and VWFA that they are called upon to both read a word and spell that same word. This result advances our understanding of the functional localization of orthography-specific representations in the brain, and the relationship between the different processes involving written language, reading and spelling, both of which are acquired skills with significant educational relevance.

Acknowledgments

This work was supported by the NICHD (R01HD056107), NIDCD (F31DC009545) and the NSF (SBE 0541953 Science of Learning Center at Gallaudet University). We would like to thank Maximilian Riesenhuber, David Roeltgen, Darlene Howard, and John VanMeter for their advice on experimental design, Eileen Napoliello for help with recruitment and testing, and Chloe Haviland and two anonymous reviewers for their input on the manuscript. We would also like to thank our participants for volunteering their time.

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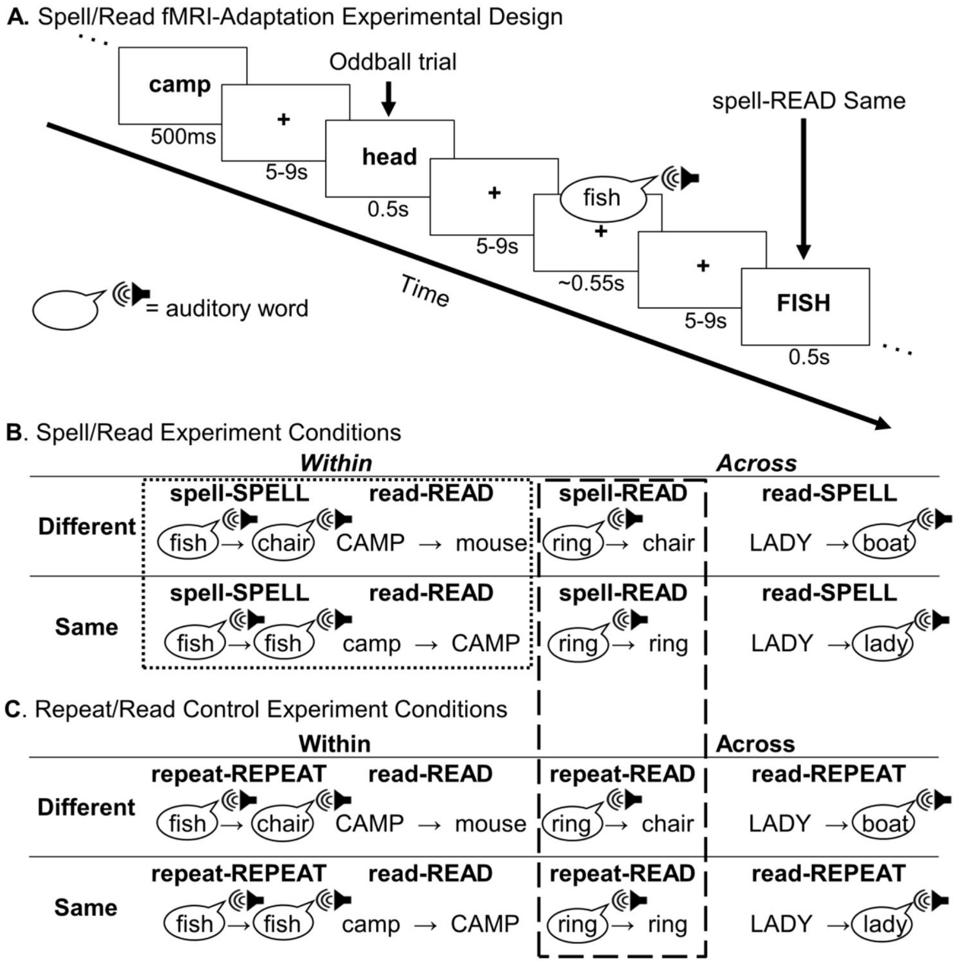

Figure 1.

(A) Continuous carry-over event-related fMRI-Adaptation design. Subjects spelled auditory words and read visual words silently. To ensure word comprehension, subjects performed a semantic odd-ball task: press the space bar for “body part” words (these trials were excluded from analysis). Conditions for both the Spell/Read Experiment (A) and the Repeat/Read Control Experiment (C) were defined by the current and just previous trial and were counterbalanced across the design in equal proportions. For each condition assignment, upper case refers to the current trial type and lower case refers to the just previous trial type, e.g. a spell-READ trial is a visual trial that was preceded by an auditory trial; this can be either the same or different word. There were two analysis approaches for the experiments in this study. The small point dotted box indicates the conditions used in Experiment 1: to identify the spatially overlapping, separately conducted *within* adaptation effects for spelling and reading. The long line dotted box indicates the conditions used in Experiment 2: identify orthography-specific adaptation effects *across* spelling and reading.

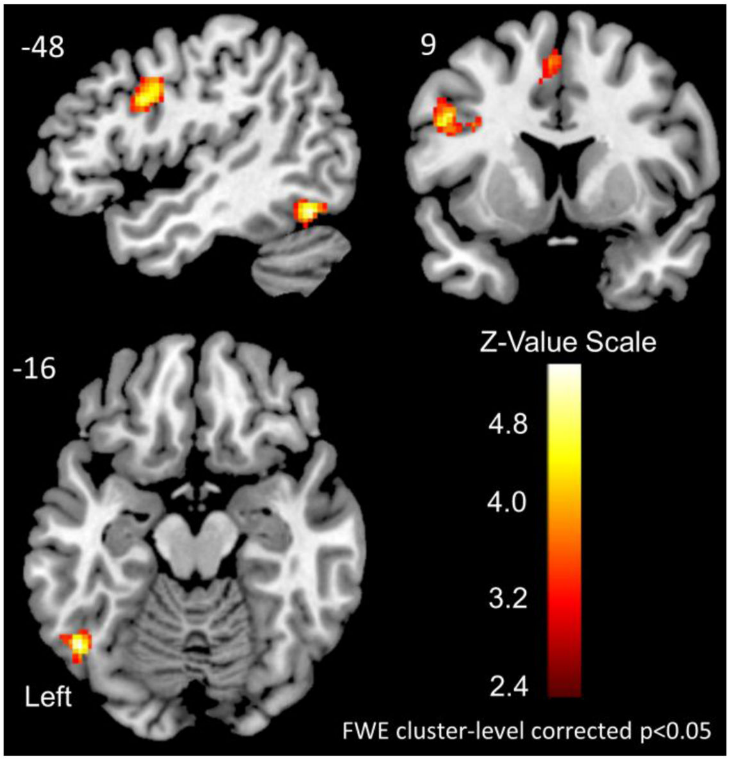

Figure 2.

Voxel-wise conjunction analysis of *within* adaptation effects for Reading and Spelling (Experiment 1). Map of clusters for the conjunction of adaptation effects (AEs) associated with the *within* read-READ and the *within* spell-SPELL conditions ($p < 0.05$, FWE cluster-level corrected). This voxel-wise analysis indicates that both spelling and reading have a shared selectivity within the left dorsal inferior frontal gyrus (BA 44/9), supplementary motor area (BA6) and mid-inferior temporal gyrus/occipitotemporal sulcus (BA 37).

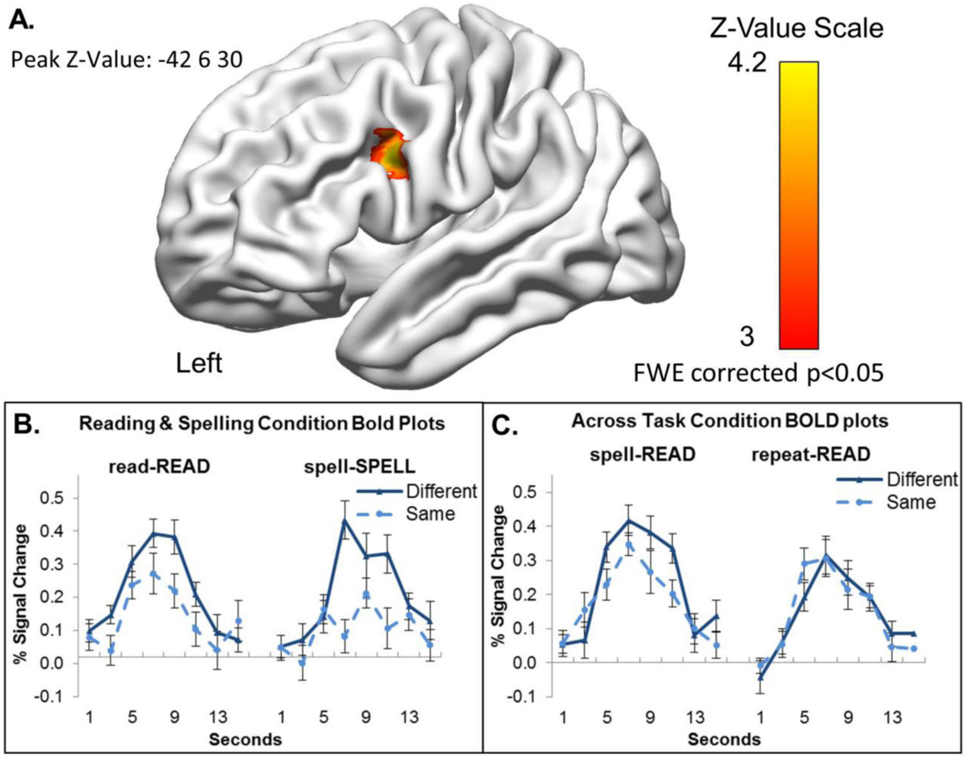

Figure 3.

A cluster in the dorsal inferior frontal gyrus (IFG) was identified in a voxel-wise analysis of the interaction effect between *across* spell-READ and *across* repeat-READ adaptation effects in Experiment 2 ($p < 0.05$, FWE cluster-level corrected); cluster size of 43 voxels and a peak z-value of 4.12 located at MNI coordinates −42 6 30. (A) Surface rendering of the dorsal IFG cluster (B) BOLD response plots of the read-READ, spell-SPELL and (C) spell-READ and repeat-READ conditions as obtained from an FIR analysis of the average signal from the dorsal IFG cluster. This is a depiction of the findings for visualization purposes only, and therefore no statistical analysis was performed on the data from these plots. The time point error is standard error of the mean. This voxel-wise analysis indicates that an area of the left IFG (BA 44/9) demonstrates shared orthographic specific processing *across* spelling and reading, and that this was not present in the repeat-READ condition.

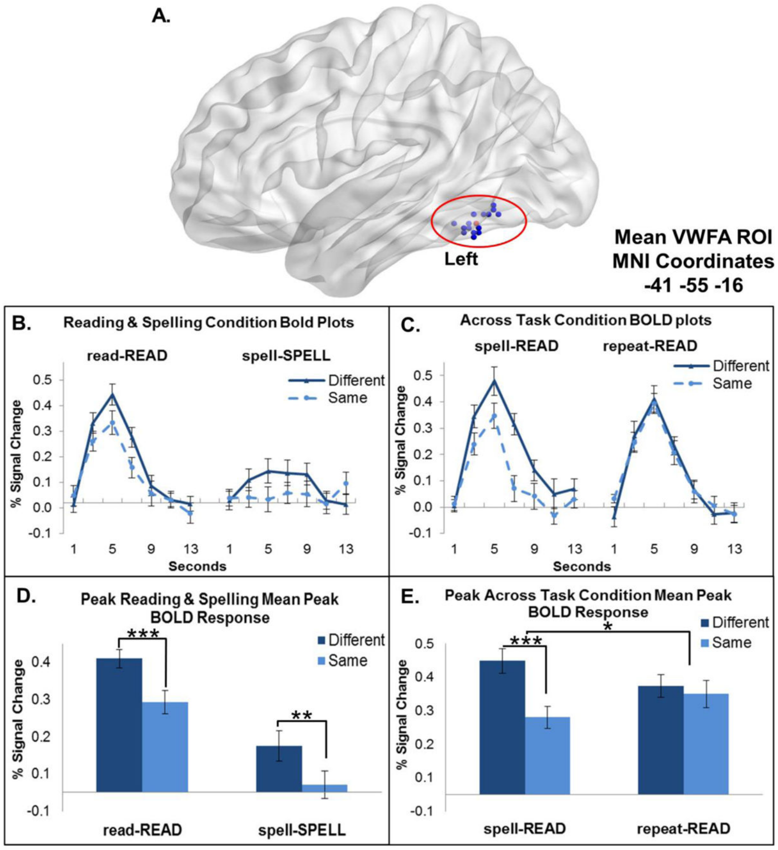

Figure 4.

The VWFA region of interest adaptation results demonstrate that it is selective to orthographic processing shared across spelling and reading. (A) The mean location of the VWFA projected onto a transparent left hemisphere standard brain. The red dot refers to the mean location of the VWFA across subjects (−41 −55 −16); the blue dots refer to the individual subject VWFA peak locations. (B) BOLD responses for each visual Read condition. Dark solid lines are different conditions. Light dotted lines are same conditions. Error bars are standard error. (C) average peak BOLD response (4–8 sec post stimulus) differences (Different-Same) for each condition. Positive values refer to an adaptation effect (i.e. Different > Same). Error bars are standard error. P-values: *** $p < 0.0001$; ** $p < 0.001$; * $p < 0.01$. These results indicate a significant effect for the read-READ, spell-SPELL, and spell-READ conditions, but critically not for the repeat-READ condition; this indicates that there are shared orthographic representations *across* spelling and reading within the VWFA.

Table 1

Adaptation Experiment Word List Parameters

	List 1	**List 2**	**Semantic List**
Word Count	180	180	44
Frequency	67 (63)	66 (60)	77 (114)
Consistency	57 (16)	56 (15)	55 (21)
Syllable #	1.5 (0.5)	1.5 (0.5)	1.2 (0.5)
Duration (ms)	539 (118)	554 (119)	571 (119)
% Right Hand Use	42% (17%)	43% (20%)	49% (22%)

Means with standard deviations in parentheses

Table 2

VWFA Peaks

Participant	**x**	**y**	**z**
1	−48	−56	−18
2	−40	−54	−20
3	−46	−50	−18
4	−42	−56	−20
5	−40	−50	−20
6	−42	−62	−8
7	−36	−52	−18
8	−42	−58	−12
9	−42	−60	−12
10	−42	−54	−22
11	−46	−54	−12
12	−40	−62	−10
13	−36	−52	−18
14	−34	−52	−16
15	−38	−64	−12
16	−36	−46	−16
Mean	**−41**	**−55**	**−16**
SD	**4**	**5**	**4**

Table 3

Anatomical regions and peak coordinates for the conjunction of read-READ and spell-SPELL Adaptation Effects (Experiment 1). N = 16 ($p < 0.05$, FWE cluster-level corrected)

Anatomical Region (Estimated Brodmann's Area)			**voxels**	**Zmax**	**MNI Coordinates**		
					x	**y**	**z**
Conjunction of read-READ & spell-SPELL							
Frontal	L	dorsal IFG (BA 44/9)	223	4.95	−44	2	32
	L	SMA (BA 6)	136	4.28	−2	12	54
Occipitotemporal	L	ITG/OTS (BA 37)	78	5.18	−48	−62	−16

Note: MNI-Montreal Neurological Institute; IFG-Inferior Frontal Gyrus; SMA-Supplementary Motor Area; MFG-Middle Frontal Gyrus; OTS-Occipitotemporal Sulcus