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Do adults acquire a second orthography using their native reading network?

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ABSTRACT

Adult second language learners typically aim to acquire both spoken and written proficiency in the second language (L2). It is widely assumed that adults fully retain the capacity they used to acquire literacy as children for their native language (L1). However, given basic principles of neural plasticity and a limited body of empirical evidence, this assumption merits investigation. Accordingly, the current work used an artificial orthography approach to investigate behavioral and neural measures of learning as adult participants acquired a second orthography for English across six weeks of training. One group learned HouseFont, an alphabetic system in which house images are used to represent English phonemes, and the other learned Faceabary, an alphasyllabic system in which face images are used to represent English syllables. The findings demonstrate that adults have considerable capacity to learn a second orthography, even when it involves perceptually atypical graphs, as evidenced by performance improvements that were sustained across weeks of training. They also demonstrate that this learning involves assimilation into the same reading network that supports native literacy, as evidenced by learning related changes in orthographic, phonological, and semantic regions associated with English word reading. Additionally, we found learning patterns that varied across the two orthographies. Faceabary induced bilateral learning effects in the mid-fusiform gyrus and showed greater engagement of regions associated with semantic processing. We speculate the large graph inventories of non-alphabetic systems may create visual-perceptual challenges that increase reliance on holistic reading procedures and associated neural substrates.

1. Introduction

Reading is a relatively recent cultural invention within the timeline of human evolution. Consequently, the emergence of reading ability within an individual must rest upon experience-dependent neural plasticity that supports the emergence of skilled visual word identification. A number of studies have shown that when an individual acquires literacy for the first time, a specific portion of the left mid-fusiform gyrus, often referred to as "the visual word form area," or VWFA, becomes more specialized for the representation of

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orthographic stimuli in the learned writing system. In this study, we ask whether orthographic tuning of the VWFA in childhood lessens the flexibility of this region to represent an orthographically distant second orthography.

1.1. Neural basis of skilled reading

Skilled reading rests upon the foundational ability to quickly and accurately recognize printed word forms (Nation, 2006; Perfetti & Hart, 2002). Prior research has localized a network of brain regions that contribute to skilled native language (L1) reading (Fiez & Petersen, 1998; Joubert et al., 2004; Reuckl et al., 2015; Taylor, Rastle, & Davis, 2013). A critical component of this network is a region within the left mid-fusiform gyrus (mFG), termed the "visual word form area," or VWFA (Cohen et al., 2000; McCandliss, Cohen, & Dehaene, 2003). The VWFA is a functionally defined brain region that becomes tuned to respond to orthographic stimuli through the acquisition of literacy. The orthographic knowledge that is supported by the mFG is integrated into a broader network that supports word identification (Dehaene, 2009; Stevens, Kravitz, Peng, Tessler, & Martin, 2017). This network includes regions within the middle temporal, superior temporal, and inferior frontal cortex that have been implicated in the automatic convergence between printed word forms and their spoken names (Binder et al., 2016; Reuckl et al., 2015). The current study uses functional magnetic resonance imaging (fMRI) to investigate functional changes within components of this reading network as adults gain skill in reading an artificial orthography for English.

It is already known that the reading network undergoes experience-dependent change that can be related to individual differences in reading skill and development (McCandliss et al., 2003). For instance, literacy seems to improve early visual processing broadly and forges a strong connection between visual and phonological representations (Dehaene, Cohen, Morais, & Kolinsky, 2015). At the same time, more specialized forms of adaptation occur. Most relevant for the current work is evidence that reading experience reshapes the visual response properties of the left mFG, so that it responds more selectively to stimuli with the visual characteristics of the learned orthography, and even to items that are orthographically legal versus illegal (e.g., words and pronounceable nonwords as compared to consonant letter strings) (Baker et al., 2007). The potency of this selective tuning is indicated by the costs incurred for the representation of other types of visual stimuli. This is seen most clearly by a shift of visual face processing to the right mFG and reduced face recognition performance as literacy acquisition tunes the left mFG (Dehaene et al., 2010). Thus, literacy-induced tuning of the mFG facilitates the processing of visual forms that are perceptually similar to the graphs of the acquired orthography, but it may reduce the future capacity to use perceptually distant visual forms as functional graphemes.

Interestingly, the orthographic tuning of the mFG is sensitive to linguistic factors that differ across orthographic systems (Hirshorn, Wrencher, Durisko, Moore, & Fiez, 2016). This is seen most clearly in work contrasting the neural substrates of reading for individuals who are literate in an alphabetic versus a non-alphabetic writing system. Skilled readers of non-alphabetic systems exhibit a bilateral recruitment of regions within the mFG for orthographic analysis and representation, while readers of alphabetic systems tend to selectively recruit the left mFG (Bolger, Perfetti, & Schneider, 2005; Nelson, Liu, Fiez, & Perfetti, 2009). Readers of both alphabetic and non-alphabetic writing systems appear to use a similar set of regions to integrate print and sound knowledge (Reuckl et al., 2015). This suggests that neural plasticity accommodates to the impact of linguistic differences, while orthographic knowledge is similarly assimilated into the spoken language system.

1.2. The capacity and flexibility of adult orthographic learning

The current paper builds on this prior work, by examining whether the tuning of the mFG for a native orthography renders it incapable of adaptive change associated with the acquisition of a perceptually, or a perceptually and linguistically, distant second orthography. This might appear to be a trivial question, since adult learners of a second language (L2) seem to readily become skilled L2 readers. However, most of the research on second language learning involves L1 and L2 languages that use the Roman alphabet (e.g., English-Spanish bilinguals) (Abadzi, 2012; Frost, 2012). This learning context seems likely to maximize the transfer of acquired orthographic knowledge and reading procedures, because the tuning of the mFG by L1 literacy acquisition should correspond well to the L2 literacy demands. This should in turn support efficient learning of the new orthography, and therefore could obscure limitations that may emerge under more demanding learning conditions (Koda, 2005).

Indeed, principles of neural plasticity, coupled with a small but convergent set of empirical findings, call into question assumptions about the capacity and flexibility of adult orthographic learning. Turning first to neural evidence, it is known that brain maturation and experience-dependent tuning of neuronal structure and function can alter the ability of a brain region to undergo adaptive modification (Knudsen, 2004). For instance, within the visual system an early period of monocular visual deprivation can permanently alter the ability of an individual to acquire binocular vision (Banks & Aslin, 1975). The extension of these findings to orthographic learning might explain why individuals who acquire literacy for the first time in adulthood struggle to become highly skilled readers and exhibit less specialized responses to orthographic stimuli within the mFG (Abadzi, 2012; Dehaene et al., 2010).

Similarly, within the auditory system, young infants can initially distinguish between native and non-native phonemes to their spoken language. However, as they gain spoken language experience, their speech perception becomes tuned to speech sounds that are meaningful units of analysis in their native language (Kuhl, Tsao, Liu, Zhang, & De Boer, 2001). This "tuning" can be difficult to overcome in adulthood, as evidenced by the difficulty second language learners have in categorically perceiving phonemes in the second language that are not shared with their native language phoneme inventory (McCandliss, Fiez, Protopapas, Conway, & McClelland, 2002).

The extension of these findings to orthographic learning raises the possibility that the degree of perceptual similarity (e.g., overlap in graph inventory, principles of visuo-spatial organization, etc.) between an L1 and an L2 writing system will influence the capacity for orthographic learning and representation. Consistent with this prediction, there is some evidence that adults whose L1 orthography uses the Roman alphabet have difficulty acquiring perceptual fluency for Arabic writing systems (Abadzi, 2012), and that it is harder for adults to acquire an artificial orthography with a perceptually distinctive versus normative graph inventory (Moore, Durisko, Perfetti, & Fiez, 2014).

A final point to consider is that orthographic systems implement different principles for mapping orthography onto phonology and semantics. This places different demands upon visual analysis, phonological decoding, and the retrieval of stored word knowledge to support word recognition (Frost, 2012; Hirshorn & Fiez, 2014; Ziegler & Goswami, 2006). Consequently, differences in the mapping principles for an L1 versus L2 writing system may shape the brain in ways that impact L2 reading development. Support for this point comes from studies comparing the English reading skill of Korean-English versus Chinese-English bilinguals. This is an intriguing comparison because on one hand, Korean and Chinese are perceptually more similar to each other than English. On the other hand, Korean is an alphabetic system like English, whereas Chinese is a non-alphabetic system in which characters map onto syllables and units of meaning. Comparisons between these two bilingual groups have consistently shown that Chinese-English bilinguals exhibit poorer word identification as compared to Korean-English bilinguals matched on the basis of spoken language experience and ability (Akamatsu, 1999, 2002; Hamada & Koda, 2010; Wang & Koda, 2005). These differences may arise because Chinese-English bilinguals have tuned a brain network for a lexical reading procedure that is adaptive for Chinese reading but sub-optimal for an alphabetic L2 (Kim, Liu, & Cao, 2017; Pae, Kim, Mano, & Kwon, 2016; Wang, Koda, & Perfetti, 2003).

1.3. The current study

The current study examines adult orthographic learning using an artificial orthography approach, in which adult native English readers acquire basic reading proficiency in a second (artificial) orthography for English. This approach offers some unique advantages over studies of naturally occurring L2 orthographic learning in adulthood (Hirshorn & Fiez, 2014). One key advantage is that the second orthography is acquired in the context of proficient spoken language. This approximates native literacy acquisition in childhood, and allows learning differences in word recognition skill to be more clearly attributed to orthographic and reading procedure factors, as opposed to differences in general word knowledge or spoken language proficiency. A second advantage is that it provides experimental control over the perceptual and linguistic properties of the assigned orthography, as well as individual's reading experiences with the new orthography. This makes it possible to disentangle factors that are often confounded in studies of naturally occurring L2 reading development.

More specifically, in this study we use neural and behavioral measures to study two groups of adult monolingual participants as they learn to read words and stories printed in an artificial orthography for English. The groups are similarly challenged with learning a writing system with a perceptually atypical graph inventory. In a "HouseFont" system, the inventory comprises 35 images of houses (Martin, Durisko, Moore, Chen, & Fiez, under revision), and in a "Faceabary" system, the inventory comprises 375 face images from different individuals displaying one of 13 different emotional expressions (Hirshorn & Fiez, 2014; Hirshorn et al., 2016). The large difference in the size of the graph inventories reflects the differing mapping principles of the two orthographic systems. HouseFont is an alphabetic system, in which each house image has a specific mapping onto an English phoneme or, in a few cases, two very similar phonemes. Faceabary is a non-alphabetic system, in which each face image represents a vowel (V), consonant-vowel (CV), or vowel-consonant (VC) English syllable, or serves as a morphological unit (e.g., to denote the plurals, phonologically realized as /s/ or /z/) (Hirshorn & Fiez, 2014; Hirshorn et al., 2016). This difference in mapping principles provides an opportunity to probe for accommodation to orthographic demands but assimilation of print-sound integration. As noted earlier, this is the pattern observed in cross-linguistic comparisons of L1 reading. However, it is unknown whether similar flexibility occurs when a second orthography is mapped onto the same L1.

In forming a set of hypothesized results, we draw upon previously reported findings from the HouseFont (Martin et al., under revision), and Faceabary (Hirshorn et al., 2016) groups. These prior studies reported results after 2–3 weeks of initial training in which participants attained a foundational level of reading skill. Both prior reports described significant learning-related changes in the mFG, with left-lateralized increases in activation observed for the HouseFont group, and bilateral increases in activation observed for the Faceabary group. These results suggest that orthographic representation within the mFG remains highly malleable, even for orthographies that are perceptually and linguistically distant from those acquired in childhood. At the same time, these previous reports noted that the reading speeds for these orthographies were slower than those observed for an artificial alphabetic orthography that used more prototypical grapheme forms (KoreanFont, which uses borrowed letters from the Korean alphabet). This raised the possibility that readers might reach a ceiling that would prevent further learning advances and motivated us to follow participants from these two groups across four additional weeks of extended training. While we hypothesize that learners will continue to progress towards more proficient levels of reading skill and exhibit neural patterns similar to those observed after foundational training, this outcome is not a certainty.

Additionally, we go beyond our prior reports by investigating the response patterns within the broader reading network to visual stimuli presented in the learned orthographies. Recent work provides evidence for a "universal mapping" of orthographic representation onto a broader reading network (Reuckl et al., 2015). This leads us to hypothesize that with learning, both HouseFont and FaceFont begin to functionally engage the reading network. Further, it suggests that they should do so in a comparable manner, despite the predicted differences in the lateralization of orthographic tuning within the mFG.

2. Methods

2.1. Participants

The participants for this study are a subset of those studied by Hirshorn et al. (2016) in their report of Faceabary learning and those studied by Martin et al. (under revision) in their report of HouseFont learning. All of the subjects in these studies were invited to return for an additional four weeks of training with their respective orthography. Nine of the HouseFont and 14 of the Faceabary participants agreed to return. Six of the HouseFont and eight of the Faceabary participants completed the extended training. Data are reported for the resulting set of 14 participants (11 female, 3 male), all of whom were native English speakers with no history of secondary language acquisition, hearing or vision issues, learning or reading problems, drug or alcohol abuse, mental illness, neurological issues, or fMRI contraindications (*M* age = 20 years, *SD* = 1.80). All participants provided informed consent and were compensated for their time.

2.2. Artificial orthography training

2.2.1. Foundational training

Before their participation in this study, all participants had completed initial (foundational) training in either the HouseFont or Faceabary writing system. For HouseFont participants, this training occurred over a two-week period. In the first week, participants learned the English phoneme represented by each house image, and then they used this knowledge to decode ("sound out") the pronunciation of English words printed in HouseFont. In the second week, participants read aloud a series of beginning reader stories printed in HouseFont. For further details, see Martin et al. (under revision). For Faceabary participants, the training occurred over a three-week period because Faceabary has a much larger graph inventory. During the first two weeks, participants learned which English syllable was represented by each face grapheme and used this to decode words in Faceabary. This was followed by a third week in which the participants read aloud the same series of beginning reader stories as the HouseFont participants, but in this case the stories were printed in Faceabary. For further details, see Hirshorn et al. (2016).

2.2.2. Extended training

Due to academic scheduling constraints, there was a variable delay between the end of each participant's foundational training and the beginning of their extended training. For this reason, all participants were required to review the grapheme-phoneme or grapheme-syllable correspondences for their assigned orthography using a self-paced computer tutor. Participants had to score 90% or better on a test of their graph-sound knowledge before commencing extended training. For the extended training, participants read aloud stories printed in their assigned orthography. The stories were taken from leveled reading materials intended for grades K-3 English reading instruction (Beck et al., 2003, 2005, 2007; Farr et al., 2000; Reading A-Z, 2008). They were transcribed into HouseFont or Faceabary and sequentially presented such that new material gradually increased in length and complexity. To encourage the development of fluent reading, repeated stories were interleaved with new material. All reading practice was done independently outside of the laboratory using materials contained on flash drives. These were provided to each participant along with instructions on the assigned reading schedule. Each of the four weeks of training included five days of story reading, each requiring approximately 15–150 min reading time, and two days of break. During each day of story reading, participants read aloud a predetermined set of stories, using a digital recorder to capture their spoken reading performance. Table 1 summarizes the training protocol.

2.3. Behavioral assessment of training

Participants completed several assessments of their skill in reading their assigned orthography; the three most relevant to this paper's aims are reported here. The first assessment (foundational assessment) occurred on the same day that a participant completed foundational HouseFont or Faceabary training. Details of this assessment are described in Martin et al. (under revision) and Hirshorn et al. (2016). The second assessment (retention assessment) occurred the day before participants commenced extended training. The third assessment (extended assessment) occurred the day after a participant completed extended training. Each assessment had a different mix of tasks, though there was substantial overlap. Table 1 summarizes the composition of each assessment and task details are provided below.

2.3.1. Grapheme knowledge

Tests of grapheme knowledge were administered multiple times as part of the extended training. For each test, participants viewed a list of 35 graphemes printed in their assigned orthography, and they were instructed to say aloud the corresponding phoneme (HouseFont) or syllable (Faceabary). The same grapheme list was used for each test session, with the exception that the order of the items varied each time.

2.3.2. Word reading

Tests of word reading were administered multiple times as part of the extended training. For each test, participants were presented with three pages, each of which contained 20 stimuli printed in their assigned orthography. The items on a given page were words that had been encountered at least once during foundational training, words that were previously unseen, or pronounceable

Table 1
Foundational and extended assessment and training schedule.

Week	*Session*	*Tasks*
Foundational Assessment		Reading Fluency (GORT A, Stories 1–6) fMRI
Retention Assessment		Word Naming Test Reading Fluency (GORT B, Stories 1–7)
Week 1	Session 1	Stories: Level 1.1 #1–5[a] Stories: Level 1.2 #1–5
	Session 2	Stories: Level 2.1 #1–5[a] Stores: Level 2.2 #1–5
	Session 3	Stories: Level 3.1 #1–5[a] Stories: Level 'Independent' #1–3
	Session 4	Stories: Level 4.1 #1–5[a] Stories: Level 'Independent' #6–8
	Session 5	3 Leveled Passages D, K, Q Grapheme Test 1† Word Reading Test 9
Week 2	Session 6	Stories: Level 1.2 #1–5 Collections – Story 1
	Session 7	Stories: Level 2.2 #1–5 Collections – Story 3
	Session 8	Stories: Level 'Independent' #1–3 Trophies 1–4 – Story 1
	Session 9	Stories: Level 'Independent' #6-8 Trophies 1–4 – Story 2
	Session 10	3 Leveled Passages D, K, Q Grapheme Test 2† Word Reading Test 10
Week 3	Session 11	Collections – Story 1 Trophies 1–5 – Story 1
	Session 12	Collections – Story 3 Trophies 1–5 – Story 3
	Session 13	Trophies 1–4 – Story 1 Trophies 2-1 – Story 2
	Session 14	Trophies 1–4 – Story 2 Trophies 2-1 – Story 4
	Session 15	3 Leveled Passages D, K, Q Grapheme Test 3† Word Reading Test 11
Week 4	Session 16	Trophies 1–5 – Story 1 Trophies 2-2 – Story 1
	Session 17	Trophies 1–5 – Story 3 Trophies 2-2 – Story 4
	Session 18	Trophies 2-1 – Story 2 Trophies 3-1 – Story 1
	Session 19	Trophies 2-1 – Story 4 Trophies 3-1 – Story 4
	Session 20	3 Leveled Passages D, K, Q
Extended Training Assessment		Grapheme/Phoneme Test† GORT A, Stories 7-10 Naming Task PALPA† fMRI

[a] Indicates that the story was read in foundational training; †results not reported in this manuscript.

nonwords that had never been seen. Participants were instructed to read the items on each page as quickly and accurately as possible, while digitally recording their reading performance. Reading fluency was determined by measuring how long it took a participant to read the entire list of 20 words, regardless of errors. Reading accuracy was calculated as the percentage of words a participant read correctly.

2.3.3. Naming task

A naming task was administered in the retention and extended assessment sessions. For this task, participants were instructed to read aloud a set of presented items as quickly as they could without making any errors. The stimuli were 109 English words transcribed in each participant's assigned orthography. In addition to being selected to vary based on design feature differences between Faceabary and Housefont (e.g., complex CCV graphs or grammatical markers in Faceabary) that are beyond the scope of the current paper, they varied along psycholinguistic dimensions that affect word recognition. These were the number of graphs in each word (i.e., word length, a sublexical factor associated with phonological decoding), and the concreteness of the transcribed English word (a lexical factor associated with semantic processing) (Brysbaert, Warriner, & Kuperman, 2014). The task administration was computer-based. Each trial began with a 500 ms fixation cross, followed by the stimulus. The stimulus remained on screen until the participant pressed the space bar to indicate they had completed reading the word aloud. The reaction time was recorded from this button press. Pressing the space bar also caused the item to be replaced by a fixation cross, which cued participants to press a button when they were ready for the next trial. Accuracy was coded offline from a digital recording of the participant's overt responses.

2.3.4. Passage reading

For a test of passage reading, participants read aloud passages of the Gray Oral Reading Test – 4 (GORT-4) (Wiederholt & Bryant, 2001) that had been transcribed into their assigned orthography. After reading each passage, they answered a set of comprehension questions. The task was administered in a pen and paper format, and participants' oral reading was digitally recorded for later scoring of reading times and accuracy. The comprehension questions were read aloud by the experimenter. Participants circled one of 5 choices they felt best answered each question. By selecting stories that varied in difficulty level and by drawing upon the two matched forms of the GORT-4 instrument, we avoided repeating a story across assessments (see Table 1). The data from the transcribed GORT-4 yielded a measure of participants' fluency (expressed as words per minute) and accuracy (expressed as errors per word) for each GORT-4 story. The GORT stories are designed to increase in difficulty and to give comparable results across the two testing forms.

2.4. Neuroimaging assessment of training outcomes

As part of the initial HouseFont and Faceabary training protocols, participants completed two magnetic resonance imaging (MRI) imaging sessions: one immediately before they commenced training (untrained session), and immediately after they completed training (foundational session). Participants completed a third scanning session immediately after they completed their extended training (extended session). The stimulus materials and scanning protocols were identical across all three sessions and followed the design used by Moore et al. (2014). In brief, participants viewed 140 words printed in either HouseFont or Faceabary and an untrained artificial orthography in which images of Korean letters are used to represent English phonemes (KoreanFont). They also saw 16 pattern displays that were repeated over 140 trials. Word and pattern stimuli were matched for length. Participants completed two runs, which consisted of seven blocks of each stimulus type for a total of 21 blocks. Each block contained 10 trials of the same stimulus type. For each trial, participants saw one word in their trained orthography, one word in KoreanFont, or one pattern set for 1500 ms, followed by 500 ms of a centrally located fixation cross. To ensure that the instructions were identical for all three scans and for all the stimuli shown, participants were instructed to attend to the stimuli rather than to perform an overt task. Participants were not exposed to this set of HouseFont or Faceabary words at any other time during training. Additional details are provided in Martin et al. (under revision) and Hirshorn et al. (2016).

2.4.1. Data acquisition

MRI data were acquired using a 3 T S Allegra equipped with a standard radio frequency coil. Following the acquisition of structural (T2, MPRAGE) volumes, functional data (fMRI) were collected across 38 interleaved slices ($3.125 \times 3.125 \times 3.2$ mm voxels) parallel to the anterior posterior commissure (TR = 2000 ms, TE = 25 ms, FOV = 200 mm, FA = 70°).

2.4.2. Data preprocessing

The fMRI data were preprocessed with the Analysis of Functional NeuroImages (AFNI) software package (Cox, 1996). The functional images were slice time corrected (3dTshift), and all data were motion corrected (3dvolreg). Motion estimates were included in the general linear model for the group analysis (3dDeconvolve). The first brain volume collected during the functional runs was removed to allow for stabilization of the signal. Functional images were scaled to a mean global intensity and smoothed using a Gaussian filter set to a smoothing kernel of 5.5 mm full width at half maximum. Next, the functional images were registered to the skull stripped high-resolution structural images. Because an MPRAGE was not collected for the Extended session, the functional runs were registered to the MPRAGE from the Retention session using AFNI's "enormous move" image registration option and manually inspected to ensure good alignment was achieved. Images were then transformed into standard Talairach space (Talairach, Tournoux, Musolino, & Missir, 1992) using a non-linear warping procedure in AFNI to allow for group analysis.

2.4.3. Regions of interest identification

Our previous reports of HouseFont and Faceabary learning focused on orthographic effects within the left and right mFG after foundational training. We found evidence for left-lateralized learning effects within the mFG (at or near the VWFA) following training with HouseFont (Martin et al., under revision). For Faceabary, we observed bilateral orthographic learning effects within the mFG (Hirshorn et al., 2016). In the current study, we examine whether this pattern persists following extended training, and whether learning-related changes can be observed within the broader neural network for reading. Because our sample size is relatively small, we used an *a priori* regions-of-interest (ROI) approach for data analysis.

To identify ROIs associated with reading, we began with reading-related regions of activation identified in prior work (Alvarez &

Table 2
Regions-of-interest within a neural network for reading.

Cortical Locations	*Center of Mass (x,y,z)*		
Orthographic regions			
L Mid-fusiform Gyrus (BA 37)	−43	−50	−16
R Mid-fusiform Gyrus (BA 37)	43	−50	−16
Phonological regions			
L Inferior Frontal Junction (BA 9)	−46	13	28
L Precentral Gyrus (BA 6)	−53	2	46
L Postcentral Gyrus (BA 3/4)	−53	−9	47
Semantic regions			
L Middle Temporal Gyrus/Superior Temporal Gyrus (BA 22)	−56	−39	4
L Inferior Frontal Gyrus (ventral) (BA 46)	−46	33	2
L Inferior Frontal Gyrus (triangularis) (BA 45)	−53	22	17
L Superior Frontal Gyrus (BA 6)	−4	12	59

Note: The orthographically biased regions were verified using a reverse inference search of NeuroSynth. Phonologically and semantically biased regions were based upon meta-analytic results reported by Alvarez and Fiez (under revision). All regions were 6 mm radius spheres with the center of mass listed. Coordinates are in MNI space. BA = Brodmann's Area (nearest).

Fiez, under revision) and then classified them as having an orthographic, phonological, or semantic processing bias. The prior work used published meta-reviews of reading, and meta-analytic maps of reading, phonology, and semantic processing available within the NeuroSynth platform (Yarkoni et al., 2011) to determine consensus regions of activation. The identified regions (see Table 2) included a left mFG cluster in the expected locus of the VWFA. A Neurosynth search found that the peak voxel location of the mFG cluster is highly associated with the terms "orthographic" (z-score = 12.59) and "visual word" (z-score = 12.16), leading us to classify it as an orthographic biased region. The remaining regions were defined as phonologically (N = 3) or semantically (N = 4) biased, based on a comparison of NeuroSynth z-scores for the phonological and semantic term list maps.

The center-of-mass of the identified regions were used to define corresponding spherical ROIs with a radius of 6 mm (33 voxels in volume). Additionally, a right mFG ROI was centered upon the mirrored loci of the left mFG ROI. The semantic and phonological ROIs were combined into separate networks using the AFNI 3dcalc function. Using AFNI 3dROIstats, the averaged beta weight value for the voxels within each network or ROI was obtained for each participant's response to their assigned orthography and KoreanFont for each scanning session. To assess the response to English words in the networks and regions, data obtained in a localizer scan that was performed as part of initial training was extracted for the subjects who did not complete the extended training (n = 6) (see Martin et al. (under revision) for more details). The beta weight values were exported to IBM Statistical Package for the Social Sciences (SPSS) version 23 to test for statistically significant differences across training at the group level using ANOVAs and other statistical tests as relevant. A significance threshold of $p < .05$ was used, with correction for all violations of normalcy in the data.

3. Results

3.1. Behavioral results

3.1.1. Grapheme knowledge

Not all participants were able to correctly produce the corresponding sound for each grapheme in their assigned orthography prior to commencing extended training. This was especially true for Faceabary, which has a much larger graph inventory than HouseFont (375 vs. 35 graphs). We used the grapheme knowledge test to investigate improvements in accurate grapheme-sound correspondence knowledge over the course of extended training. A 2 × 3 ANOVA showed a significant main effect of group, with the HouseFont group (M = 0.97, SE = 0.05) performing more accurately than the Faceabary group (M = 0.76, SE = 0.05), $F(1,12) = 9.17$, $p = .01$, $\eta_p^2 = 0.43$. There was no significant interaction or effect of session, $ps < .041$; however, both groups exhibited a 3.5% increase in accuracy by the third test.

To better understand the errors made by the Faceabary participants, we first determined whether the errors consisted of producing a syllable with an incorrect consonant, an incorrect vowel, or both. We found that consonant-only and consonant-vowel errors accounted for a small fraction of the total errors (11% and 9%, respectively), while vowel-only errors were a large fraction (79%). To explore the vowel errors in greater depth, we constructed a confusability matrix contrasting the expected vowel versus the produced vowel for each of the items in the grapheme test. The most common vowel errors were: (1) a substitution of /æ/ for /ʊ/, which are represented by a neutral facial expression and a calm facial expression, respectively; and (2) a substitution of /ɔ,ɑ/ (one of the few cases in which two similar phonemes are represented by one facial expression) for /ɛ/, which are represented by a fearful facial expression and a surprised facial expression, respectively. Previous work with the face images used in Faceabary has shown that the calm and neutral expressions, as well as the surprise and fear expressions, are particularly difficult to distinguish from each other (Tottenham et al., 2009). Taken together, these results suggest that the poorer grapheme test performance of the Faceabary participants is largely caused by the perceptual challenge of discriminating between highly confusable facial expressions, and not a difficulty in simply memorizing a large set of graph-sound correspondences.

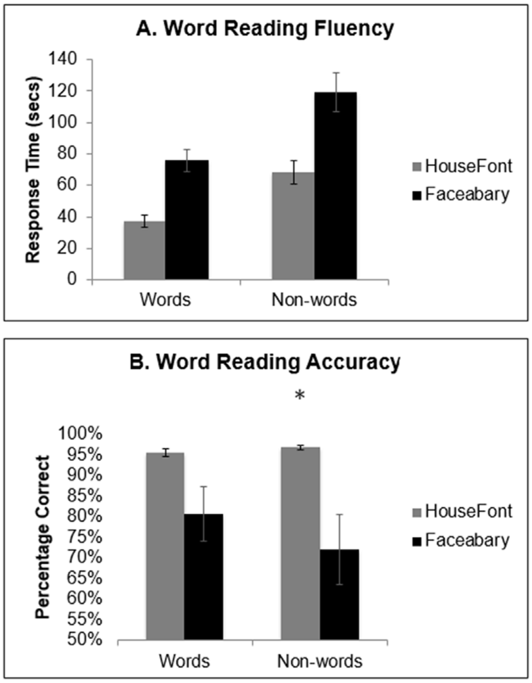

Fig. 1. Performance on the word reading tests administered during extended training.
Top graph (A) shows the mean time required to read 20 words or nonwords printed in a participant's assigned orthography. Bottom graph (B) shows the mean percent of correctly pronounced words or nonwords in each 20-item list.

3.1.2. *Word reading*

A further question of interest is whether participants show evidence of accommodation to the impact of linguistic differences. To address this question, we examined lexical influences on word reading performance measured during training (Fig. 1). To increase power, we collapsed the reading task data across testing sessions, and also across the two word conditions (old and new). We then implemented 2 × 2 ANOVAs on the fluency and accuracy measures, with Group (HouseFont, Faceabary) as a between subjects factor and Word Type (Words, Nonwords) as a within subjects factor. HouseFont participants were faster and more accurate than Faceabary participants, *ps* ≤ .04. There was also a main effect of Word Type for both response time and accuracy such that reading was faster and more accurate for Words compared to Nonwords, *ps* < .02. The Word Type × Group interaction was non-significant for fluency, $F(1,12) = 2.40$, $p < .15$, $\eta_p^2 = 0.17$, but was significant for accuracy, $F(1,12) = 15.13$, $p < .01$, $\eta_p^2 = 0.56$. Pairwise comparisons revealed this interaction was driven by more accurate reading of Words compared to Nonwords for Faceabary participants, $p = .03$, whereas HouseFont participants showed a marginally significant trend of reading Nonwords more accurately than Words, $p = .08$.

3.1.3. *Word naming task*

To further explore accommodation effects, we investigated lexical and sublexical influences on word naming before and after extended training. Specifically, we used linear mixed effects models to understand the impact of our lexical (Concreteness) and sublexical (Word Length) factors on reaction times in the naming task. All incorrect trials were removed. Both models included fixed effects of Group (HouseFont vs. Faceabary), Assessment (Retention vs. Extended), and either Concreteness or Word Length. For the model including Concreteness, only nouns were examined. The model including Word Length used data from all types of words. Both stimulus factors were mean-centered. Each model also included random intercepts for individual words, and participants. The models were fit using the R software (R Development Core Team, 2008) and the lme4 package (Bates, Maechler, & Dai, 2008).

For the analysis of lexical effect, the results indicated main effects of Group, Session, and Concreteness on word naming times (Fig. 2, Table 3). There were significant 2-way interactions between Group × Session, and marginal interaction between Group × Concreteness, such that reaction times (RTs) were more affected by Concreteness (e.g., shorter RTs for more concrete words) in the Faceabary group. There was no significant 3-way interaction between Group × Session × Concreteness.

For the analysis of sublexical effect, results indicated main effects of Group, Session, and Word Length on RTs (Fig. 2, Table 4). There were significant 2-way interactions between Group × Length, Group × Session, and Session × Length. Of special interest was the Group × Length 2-way interaction, such that RTs were more affected by Length (e.g., longer RTs for longer words) in the HouseFont group. There was also a significant 3-way interaction between Group × Session × Length, such that the greater influence of Length on RTs in the HouseFont group was larger in the Extended compared to Retention assessment of word naming.

3.1.4. *Passage reading*

A central question of this study is whether participants exhibited ceiling effects in learning. To address this question, we used the

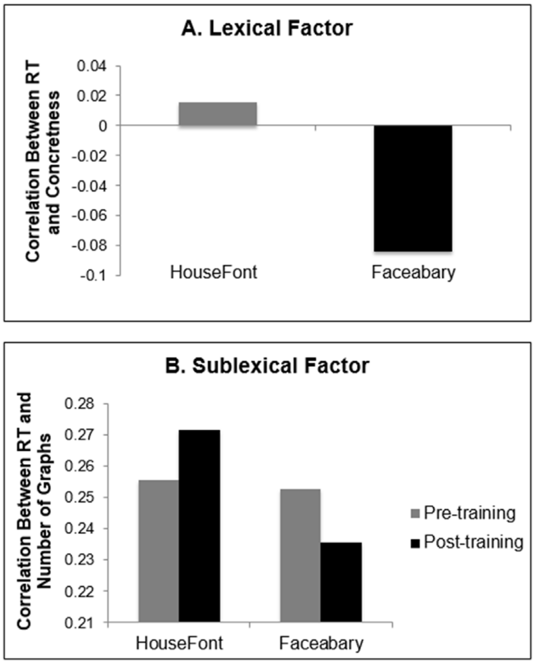

Fig. 2. Lexical and sublexical influences on word naming after extended training.
Interaction effects are shown for a regression analysis examining group (HouseFont, HF; Faceabary, FB) differences in the effects of a lexical (Concreteness) and a sublexical (Word Length) factor on word naming response times (RT), before and after extended training. Top graph (A) shows the marginally significant Group × Concreteness interaction. Bottom graph (B) shows the significant Group × Session × Length interaction. For visualization purposes, zero-ordered correlations are displayed, not model estimate parameters.

Table 3
Results of linear mixed model including concreteness.

	Estimate	*Std. Error*	*t value*	*Significance*
(intercept)	38804	7135	5.44	***
Group	−31226	7471	−4.18	***
Session	−16238	4287	−3.78	***
Concreteness	−11336	5296	−2.14	*
Group × Session	14061	4556	3.09	***
Group × Concreteness	10825	5606	1.93	–
Session × Concreteness	5287	3193	1.66	
Group × Session × Concreteness	−4989	3440	−1.45	

- = $p < .10$, * = $p < .05$, *** = $p < .001$.

Table 4
Results of linear mixed model including Word length.

	Estimate	*Std. Error*	*t value*	*Significance*
(intercept)	21677	816	25.57	
Group	−15855	1335	−11.88	***
Session	−8448	365	−23.12	***
Length	5819	589	9.88	***
Group × Session	6912	618	11.18	***
Group × Length	−5121	752	−6.81	***
Session × Length	−2487	357	−6.96	***
Group × Session × Length	2256	472	4.78	***

*** = $p < .001$.

GORT data to evaluate participants' continued growth in learning from foundational through extended training. Specifically, we performed 2 × 2 ANOVAs on the fluency and accuracy measures for GORT-A Story 6 (the most difficult story read as part of the foundational assessment) and GORT-A Story 7 (the simplest story read as part of the extended assessment), with Group (HouseFont, Faceabary) as a between subjects factor and Assessment (Foundational, Extended) as a within subjects factor. Both groups showed

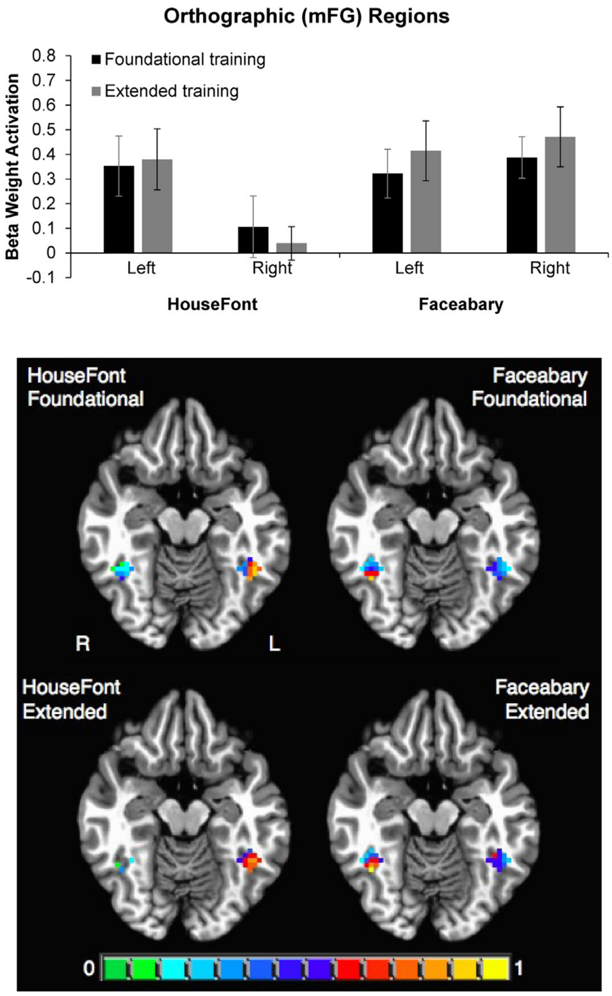

Fig. 3. mFG responses to the HouseFont and Faceabary orthographies after training.
The graph shows neural activation (estimated beta weights) for left and right mFG ROIs, for participants' assigned orthography after foundational and extended training. The two orthographies elicited comparable responses in the left mFG, but there was a significant difference, *p* = .03, in activation in the right fusiform gyrus between Faceabary and HouseFont reading. Error bars represent standard error. The activation maps show the left and right mFG ROIs (z = −18 MNI) for HouseFont and Faceabary.

increases in fluency from the foundational to the extended assessment, $F(1,12) = 7.95$, $p = .02$, $\eta_p^2 = 0.40$, and HouseFont participants were faster than Faceabary participants, $F(1,12) = 9.42$, $p = .01$, $\eta_p^2 = 0.44$. There was no Group × Assessment interaction, $p = .16$. Accuracy improved from the foundational to the extended assessment for both groups, $F(1,12) = 6.39$, $p = .03$, $\eta_p^2 = 0.35$. A significant interaction was observed for reading accuracy, $F(1,12) = 6.33$, $p = .03$, $\eta_p^2 = 0.35$, such that Faceabary participants were less accurate than HouseFont participants during the foundational assessment, but improved during extended training to reach similar levels of accuracy in the extended assessment.

3.2. Neuroimaging results

3.2.1. Learning effects in the left and right mFG

The first set of analyses focused on the left and right mFG ROIs. Previous work demonstrated orthographic learning effects in the mFG (left-lateralized for HouseFont, bilateral for Faceabary) following Foundational training. Thus, the question of interest in this study is whether extended training induced further learning effects. To address this question, a 2 × 2 × 2 mixed-design ANOVA was performed on the mean mFG activation. Laterality (Left, Right) and Session (Foundational, Extended) were entered as within subjects factors, and Orthography (HouseFont, Faceabary) was entered as a between subjects factor. None of the main effects or interactions were significant, with the exception of a marginally significant Laterality × Orthography interaction, $F(1,12) = 3.94$, $p = .07$, $\eta_p^2 = 0.25$. Pairwise comparisons revealed that the interaction was driven by significantly higher activation ($p = .03$; Fig. 3) in the right mFG for Faceabary (M = 0.43, SE = 0.10) as compared to HouseFont (M = 0.07, SE = 0.11). Based on these results, it appears

Table 5
T-test means for trained orthographies and KoreanFont before and after training.

Network	*Group*	*Response Category*	*Mean Beta Weight (SD)*
Semantic			
	HouseFont		
		Untrained	.04 (.13)
		Trained	.07 (.11)
		KoreanFont Untrained	.00 (.09)
		KoreanFont Trained	.01 (.05)
	Faceabary		
		Untrained	.06 (.09)
		Trained	.25 (.20)*
		KoreanFont Untrained	.04 (.15)
		KoreanFont Trained	.09 (.07)
Phonological			
	HouseFont		
		Untrained	.06 (.27)
		Trained	.56 (.32)**
		KoreanFont Untrained	.08 (.16)
		KoreanFont Trained	.10 (.13)
	Faceabary		
		Untrained	.04 (.12)
		Trained	.53 (.35)**
		KoreanFont Untrained	.08 (.18)
		KoreanFont Trained	.12 (.10)

Significant differences (paired *t*-test) between the trained and untrained conditions are marked by "*"($p < .05$) or "**"($p < .01$) and were observed in the semantic network only for Faceabary, and in the Phonological network for both HouseFont and Faceabary.
For all statistics the trained value is an average of foundational training and extended training.

that the left mFG is engaged by both fonts, while the right mFG is selectively active during Faceabary reading (Fig. 3). The lack of a main effect of Session, as well as a three-way interaction involving Session, indicates that there was no meaningful change in neural activation within the mFG from Foundational to Extended training.

3.2.2. *Effects of initial training on the reading network*

In our prior work little attention was paid to the reading network beyond the mFG. For this reason, we began by determining whether learning-related changes could be observed in our phonological and semantic ROIs. A paired sample *t*-test was performed for HouseFont and Faceabary across the ROIs in our phonological and semantic networks, by contrasting activation before any training and after training (the averaged response across the Foundational and Extended sessions) (see Table 5). HouseFont participants had a significantly higher response to HouseFont words in the phonological reading network after training, $t(5) = -5.15$, $p = .004$. The response to HouseFont words was not significantly different between untrained and trained in the semantic reading network, $t(5) = -0.60$, $p = .57$. Faceabary learners demonstrated a significantly higher response to Faceabary words after training in both the phonological, $t(7) = -4.49$, $p = .003$, and semantic reading networks, $t(7) = -3.24$, $p = .01$. This pattern of results suggests that after training, HouseFont reading specifically recruits phonological regions, whereas Faceabary reading recruits both phonological and semantic regions (Fig. 4).

To ensure that the observed activation changes across training for HouseFont and Faceabary were unique to the trained orthographies, the response to an untrained orthography, KoreanFont, was tested for all participants. Four similar paired sample t-tests were performed with the dependent variable of interest being the mean response to KoreanFont words (Table 5). None of the comparisons were significant $ps > .47$. These results support the idea that learning to read a second orthography induces specific changes in reading related regions.

3.2.3. *Effects of extended training on the reading network*

To assess how additional training might alter the activation for participants' assigned orthography, separate mixed design 2 × 2 ANOVAs were performed for the phonological and semantic reading networks with Group (HouseFont, Faceabary) as a between subjects factor and Session (Foundational, Extended) as a within subjects factor.

There were no significant main effects or interactions for the phonological or semantic networks, however, the between subjects factor of Group failed Levene's Test of equality of error variances for the extended training scores ($p = .01$). To assess if group differences existed, an independent samples *t*-test was performed on Group by collapsing across Session and using the equal variances not assuming correction.

Collapsing across Foundational and Extended training revealed a trending effect of Group in the semantic reading network, $t(11.38) = -2.11$, $p = .06$, such that Faceabary (M = 0.25, SD = 0.20) had a higher mean activation than HouseFont (M = 0.07, SD = 0.11). The lack of a Session effect in the semantic network is consistent with the findings in the phonological network, and suggests that increased training does not further increase activity in reading related regions beyond that observed following foundational training. The finding that Faceabary reading may cause more activation within the semantic reading network is consistent

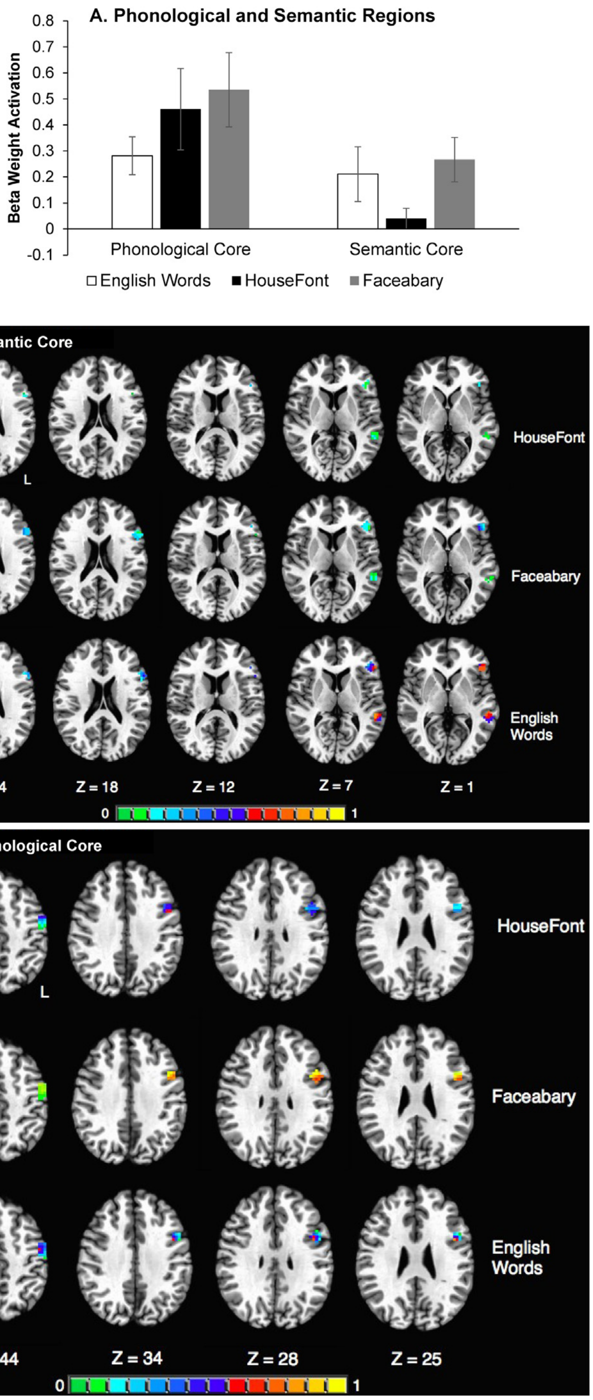

Fig. 4. Responses to the trained orthographies (and English words) in reading-related regions. A) The neural response in the phonological and semantic ROIs for the trained orthography during the extended training assessment. Error bars represent standard error. For qualitative comparison, also shown is the response to printed English words, as measured in the subset of HouseFont participants who did not advance beyond foundational training (Martin et al., under revision), using a localizer protocol with differing stimulus presentation parameters. B) Activation maps for the semantic network ROIs for the trained orthography and English words (measured in the subset of HouseFont participants who did not advance beyond foundational training). C) Activation maps for the phonological network ROIs for the trained orthography and English words (measured in the subset of HouseFont participants who did not advance beyond foundational training).

with the *t*-test results reported earlier, as only Faceabary participants demonstrated a significant increase in the semantic reading network after Foundational training. Overall, this result reinforces the conclusion that the semantic reading network is recruited to a greater extent when reading Faceabary as compared to HouseFont.

4. Discussion

The current study examined adult orthographic learning using an artificial orthography approach. We used behavioral and neural measures to probe for learning-related changes in participants who devoted 6–7 weeks to learning one of two perceptually atypical artificial orthographies for English: an alphabetic HouseFont system in which individual house images represent English phonemes, and a syllabic Faceabary system in which individual face images represent English syllables. The study builds upon previous reports involving these two groups of participants (Hirshorn et al., 2016; Martin et al., under revision) as well as participant groups who trained with one of two other alphabetic artificial orthographies (FaceFont and KoreanFont, in which face images or borrowed letters of the Korean alphabet, respectively, represent English phonemes) (Moore et al., 2014). In all of these prior studies, learning effects were assessed after a relatively short period of training (two or three weeks). This left open three important questions: 1) Do adult learners reach a performance ceiling for orthographically distant writing systems? 2) Does learning involve the same reading network that supports L1 literacy? 3) Does learning accommodate the impact of linguistic differences between writing systems? We consider how the results from this study provide an answer to each of these questions.

4.1. *Do adult learners reach a performance ceiling?*

In our prior work, we demonstrated that adult native English speakers are able to acquire basic proficiency with a second orthography for English in as little as two weeks (Hirshorn et al., 2016; Martin et al., under revision; Moore et al., 2014). However, the attainment of basic proficiency does not guarantee that a learner is on a trajectory toward fluent adult reading. In other words, a performance ceiling that does not apply to children acquiring literacy for the first time could restrict adult learning. This ceiling could be imposed by reductions in neural plasticity associated with brain maturation per se, or by experience-dependent tuning of the brain to the properties of a native orthography (Abadzi, 2012; Dehaene et al., 2010).

By continuing training for another four weeks, the current study gained further insight into the trajectory of adult learners of a second orthography. The behavioral reading assessments found continued growth in reading skill with no evidence of a performance plateau for either participant group. Indeed, the gains in fluency approximated those seen after 3 months of early reading instruction (Hasbrouch & Tindal, 2006), a noteworthy achievement given our participants invested only ~30 total hours in training. It is also striking that Faceabary participants not only became more accurate at reading passages, they also closed the gap between themselves and the HouseFont participants to reach similar levels of reading accuracy at the extended assessment.

Importantly, robust learning was observed even though the HouseFont and Faceabary orthographies use graphs that are perceptually atypical (i.e., images of houses or faces, respectively). As noted in Martin et al. (under revision), this is a non-trivial point, because it has been hypothesized that writing systems have undergone cultural evolution to align the visual properties of natural orthographies with neural constraints on visual processing (Dehaene, 2009). This can explain why orthographies around the world share common properties, such as the use of graphs comprising line segments of specific length, curvature, and spatial orientation. By this account, individuals should struggle to acquire orthographies with visual properties that differ from the cultural norm. However, the fact that adults show sustained improvement in HouseFont and Faceabary reading skill provides counter evidence to this hypothesis.

4.2. *Is the L1 reading network engaged?*

In our prior work, we demonstrated that foundational training produces learning-specific increases in the neural response to words printed in the assigned orthography. Our analyses focused on category-biased areas in visual association cortex, including the fusiform face area in the right mFG (Kanwisher, McDermott, & Chun, 1997), the parahippocampal place area in the bilateral parahippocampus (Epstein, Harris, Stanley, & Kanwisher, 1999), and the visual word form area in the left mFG (McCandliss et al., 2003). Across all three of our prior studies, we found compelling evidence that learning to read any of our artificial orthographies recruits neural tissue tuned by native literacy acquisition (i.e., the left mFG), and that reading skill in the assigned orthography is predicted by the strength of this neural recruitment (Hirshorn et al., 2016; Martin et al., under revision; Moore et al., 2014). These findings support claims that the mFG becomes tuned for orthographic representation because the connectional architecture of this region provides a bridge into the language network (Moore et al., 2014; Reinke, Fernandes, Schwindt, O'Craven, & Grady, 2008; Stevens et al., 2017; Vigneau, Jobard, Mazoyer, & Tzourio-Maxzoyer, 2005), and not because it is inherently specialized for particular types of visual analysis (Dehaene, 2009). The current study provides further support for this conclusion, by demonstrating that learning effects can also be found in brain regions associated with phonological and semantic aspects of reading.

The malleability of the reading network may seem at odds with the difficulties that adult learners face in becoming highly proficient in a second language. But it is perhaps to be expected, because it is estimated that the average adult reader experiences an unfamiliar word about once per page (Nation, 2006). If the neural system did not have the capacity to readily acquire and interconnect new orthographic knowledge throughout the lifespan, an individual's mental lexicon would never change or increase. The present results demonstrate that this neural capacity for orthographic learning extends beyond new words printed in a known orthography to encompass new words in a perceptually distant orthography.

This is not to deny that perceptual dissimilarity between a first and second orthography may impact learning. Indeed, in our comparison of training effects for two alphabetic orthographies that different only in the perceptual forms of their graphs (borrowed Korean letters versus face images) we found that participants exhibited more fluent reading and greater mFG activation for the orthography that used perceptually typical (KoreanFont) versus atypical (FaceFont) graphs (Moore et al., 2014). We speculated that the dissimilarity between English and FaceFont might reduce the neuronal resources available for the new orthography, which could thereby create a perceptual bottleneck that slows the identification of FaceFont word forms.

Given that our prior findings demonstrated a link between mFG activation and acquired reading skill (Hirshorn et al., 2016; Martin et al., under revision; Moore et al., 2014), we expected that further changes in neural activation would be observed across the reading network as participants gained proficiency through extended training. Counter to this expectation, significant differences were not observed between the Retention versus Extended imaging sessions even though behavioral assessments of reading speed and accuracy showed continued improvement. It is possible that repeated scanning with the same imaging paradigm and items caused an attenuation of the response (MacDonald et al., 2015; Raichle et al., 1994). However, the stability of the response to an untrained orthography (KoreanFont) makes this unlikely. Instead, we favor the idea that the neural system might be working close to capacity to support a beginning level of effortful reading. Accordingly, participants may need to gain more automaticity before further modulations in the neural response are observed (Mukai et al., 2007; Yotsumoto, Watanabe, & Sasaki, 2008), or alternative approaches to measuring neuronal tuning effects may be needed to uncover learning effects (Gotts, 2016).

4.3. Does learning accommodate the impact of linguistic differences?

A final question of interest was whether cross-linguistic similarities and differences that have been observed using natural orthographies could be replicated using an artificial orthography approach. We were particularly interested in evidence that greater left-lateralization of the VWFA is observed for alphabetic as compared to non-alphabetic orthographies (Bolger et al., 2005; Nelson et al., 2009). Our comparison of HouseFont and Faceabary provides convergent support for this pattern. Like naturally occurring alphabets that have been studied, HouseFont produced strongly left-lateralized training effects in the mFG that persisted over time. In contrast, Faceabary, like naturally occurring non-alphabetic writing systems, produced bilateral training effects in the mFG that persisted over time.

In understanding these patterns, it is noteworthy that both HouseFont and Facebary words are printed as a linear sequence of graphs. This suggests that lateralization patterns within the mFG cannot be accounted for based on the visual-spatial composition of printed words. Instead, we speculate that non-alphabetic orthographies may encourage (or necessitate) the use of lexical reading procedures, which may in turn encourage (or necessitate) the holistic analysis of visual word forms. Our behavioral results suggest Faceabary words are more reliant on holistic decoding procedures. Faceabary participants were significantly faster when reading words compared to nonwords, a pattern that was found to be reversed for HouseFont participants, and unlike HouseFont participants, Faceabary participants did not show increased reading times for longer words on the word naming task. These results would be expected if Faceabary reading encourages reliance on representing printed words holistically rather than as separable sequence of graphs. The bilateral activation found for Faceabary is also consistent with other work demonstrating a link between activation of right visual association cortex and holistic object perception (Kanwisher, Tong, & Nakayama, 1998; Maurer, Le Grand, & Mondloch, 2002).

It is also of note that we replicate a pattern of orthographic accommodation observed by Nelson et al. (2009). The Nelson et al. study involved Chinese-English bilinguals, who exhibited the typical left-lateralized mFG response to printed English words, but a bilateral mFG response to Chinese characters. Because the study involved beginning readers of Chinese, it was possible that a bilateral pattern of activation would be observed in any beginning reading group. The results of the current study, where HouseFont and Faceabary show highly divergent and stable patterns of mFG activation, cast doubt on this explanation. Instead, the results suggest that a non-alphabetic mapping principle can drive bilateral engagement of the mFG, even in adults whose L1 has tuned a left-lateralized VWFA.

In considering underlying causes for this mapping principle effect, visual-perceptual demands and grapheme-sound uncertainty may play an important role. Non-alphabetic systems tend to have large grapheme inventories with many forms distinguishable only by fine-grained visual differences. This can leave beginning readers prone to perceptual discrimination errors and confusions, leading in turn to decoding errors (Nag, Snowling, Quinlan, & Hulme, 2014; Zhou, McBride-Chang, & Wong, 2014). Consistent with this interpretation, we found that many Faceabary readers exhibited imperfect performance on a grapheme-sound mapping test even after weeks of training, and they were especially prone to confuse the vowel mappings for visually confusable facial expressions. As a consequence, Faceabary readers appear to be more dependent upon lexical and semantic constraints, based upon behavioral evidence of significant effects of lexical status on naming accuracy, and concreteness on naming speed, for Faceabary but not HouseFont readers.

Moving beyond the mFG, we find intriguing evidence of both assimilation and accommodation within the broader reading network. In terms of assimilation, we observed that phonological regions in the reading network were similarly engaged by HouseFont and Faceabary. This is consistent with cross-linguistic research suggesting that phonological access is a universal principle of writing systems (Perfetti, Zhang, & Berent, 1992), and that it is mediated by a universal set of brain regions that support print-sound convergence (Reuckl et al., 2015). At the same time, we also found evidence of increased activation within semantic regions in the reading network for Faceabary but not HouseFont readers. We speculate that these effects are a consequence of the visual discrimination challenges associated with non-alphabetic systems (Hirshorn & Fiez, 2014), which as discussed above may lead readers to make errors in mapping graphs to their sound correspondences, in turn increasing their reliance upon top-down lexical constraints for accurate word recognition. Over time, this could increase the weighting of lexico-semantic processing in skilled word recognition, thus adaptively tuning a reading network in response to the perceptual challenges of a non-alphabetic orthography.

4.4. Limitation and future directions

One limitation of the current study is its modest sample size. All of the participants from the original study were invited to continue training; however, only 14 participants (six HouseFont readers and eight Faceabary readers) self-selected to return for extended training. The self-selection of this subset of the original participants may indicate that we recruited those that were more apt to perform well or to be invested in learning.

There are still many unanswered questions about the process of learning a new orthography and the associated neurobiological changes. One question of particular interest is how orthographic distance, the similarity/dissimilarity of orthographic characteristics, might support neural accommodation and alter learning. For instance, we might expect a native English reader to have an easier time learning to read Spanish than Russian because English is visually and phonologically more similar to Spanish. Conversely, there is also the possibility that the overlap between English and Spanish might hinder reading because of interference between the shared elements. By comparing and contrasting how such visual and phonological differences and similarities impact learning, we may be able to more finely characterize the flexibility of the reading network.

Another question of interest is how reading networks are recruited in multilingual individuals learning a new script. While the existence of hyperpolyglots, people that speak dozens of languages, suggests that an upper limit on language learning may not exist, we still do not understand how the acquisition of multiple unique orthographies impacts the reading network. This is increasingly important area of future study because the number of multilingual individuals is likely to continue to rise as global communication becomes more convenient.

4.5. Conclusions

This study supported our other work and found compelling evidence that adult readers not only learned to read atypical orthographies, but that their reading ability continued to improve over several weeks of training with no indication that the participants reached a performance ceiling. Further, this novel orthographic learning recruited reading networks that underlie native language learning, with differences in activation based on the mapping principals of the orthography. More specifically, our work demonstrated that alphasyllabic learning recruited regions from both the semantic and phonological reading networks and bilaterally activated the mFG, whereas alphabetic learning relied primarily on regions within the phonological reading network and showed unilateral, left mFG activation. Our findings suggest that the unique mapping principles of our two artificial orthographies lead to differential utilization of the reading networks to optimally decode words.

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