

Neurobiological signatures of L2 proficiency: Evidence from a bi-directional cross-linguistic study

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ABSTRACT

Recent evidence has shown that convergence of print and speech processing across a network of primarily left-hemisphere regions of the brain is a predictor of future reading skills in children, and a marker of fluent reading ability in adults. The present study extends these findings into the domain of second-language (L2) literacy, through brain imaging data of English and Hebrew L2 learners. Participants received an fMRI brain scan, while performing a semantic judgement task on spoken and written words and pseudowords in both their L1 and L2, alongside a battery of L1 and L2 behavioural measures. Imaging results show, overall, a similar network of activation for reading across the two languages, alongside significant convergence of print and speech processing across a network of left-hemisphere regions in both L1 and L2 and in both cohorts. Importantly, convergence is greater for L1 in occipito-temporal regions tied to automatic skilled reading processes including the visual word-form area, but greater for L2 in frontal regions of the reading network, tied to more effortful, active processing. The main groupwise brain effects tell a similar story, with greater L2 than L1 activation across frontal, temporal and parietal regions, but greater L1 than L2 activation in parieto-occipital regions tied to automatic mapping processes in skilled reading. These results provide evidence for the shifting of the reading networks towards more automatic processing as reading proficiency rises and the mappings and statistics of the new orthography are learned and incorporated into the reading system.

1. Introduction

Achieving reading fluency in a second language is one of the foremost research concerns in the light of globalization. The integration of non-native populations into society, and especially into the workforce, is dependent upon the acquisition of functional literacy (August & Shanahan, 2006). This challenge for literacy instruction is complicated by the fact that immigration may occur at any age, producing a significant cohort of language-minority individuals who come to the task of acquiring a new language after the acquisition of literacy in their native language has matured, and by the fact that some linguistic environments of native languages are

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very different than that of English as a second language (Bialystok & Miller, 1999).

A large proportion of second language acquisition studies to date have examined cases in which the two languages come from the same language family (Dutch-English, Spanish-English, Spanish-Catalan). As such, the patterns of learning reflect the shared processing routines or shared linguistic representations from the native language (L1) supporting reading of the second language (L2). Moreover, studies that show minimal effects of late age of acquisition on attainment have often involved very similar language pairs, whereas studies that report more difficulty in attaining native-like abilities are those which have investigated more highly contrasting languages (e.g., Hungarian-English; DeKeyser, 2000; Chinese or Korean-English, Johnson & Newport, 1989). The present study focuses on literacy development in L2 learners of English and Hebrew, symmetrically investigating cohorts of native English speakers learning Hebrew and native Hebrew speakers being immersed in English. English and Hebrew provide an interesting case of contrasting languages. Both have relatively opaque alphabetic writing systems; however, they differ substantially in the morphological structure of words, in the manner in which the morpho-phonological properties of words are represented by their written forms (Velan & Frost, 2011), and they utilise different alphabets. Similarities and differences in the statistical properties of the English and Hebrew orthographies, as well as their potential to affect reading strategies, are well-documented (e.g. Lerner, Armstrong, & Frost, 2014; Pollatsek, Treiman, & Frost et al., 2015). The symmetrical comparison of L1-English L2-Hebrew vs. L1-Hebrew L2-English at both the neurobiological and cognitive levels of analysis in this study allows us to pull apart L1-L2 differences and English-Hebrew differences, providing a clearer interpretation of what is common and what is different in learning an L2 writing system given L1, and importantly, how the directionality of learning might modify L1/L2 neurocognitive pathways.

Previous cross-linguistic research indicates that skilled reading requires mastery not only of orthographic forms, but also of the structural properties of the language, including the systematic correlations among the phonological, morphological, and semantic properties of words (see Frost, 2011, for review). This suggests that literacy acquisition in L2 involves the implicit incorporation of the linguistic regularities characteristic of that language, reflected by the typical computations characteristic for processing its orthographic forms, both in terms of overt behaviour (e.g., Frost, Kugler, Deutsch, & Forster, 2005) and in their neurobiological underpinning (e.g., Bick, Goelman, & Frost, 2011; Paulesu et al., 2000). This is reflected in recent extensions of the connectionist triangle model framework to languages other than English, particularly Chinese (Yang, McCandliss, Shu, & Zevin, 2009). In general, these models have shown how such patterns might arise from the interaction of a common (language-independent) functional architecture and the language-specific patterns of statistical regularities embodied by each writing system (for related computational claims see also Lerner et al., 2014, comparing Hebrew and English). These regularities, which include reliable correspondences in the mappings from spelling-to-sound and spelling-to-meaning (the latter primarily a consequence of the morphological structure of the language) have two important consequences for the organization of the reading system. First, the ‘division of labour’ between phonological and semantic processes varies systematically across languages, with more regular spelling-sound mappings engendering greater reliance on phonological recoding, whereas richer morphological structure results in a stronger role for orthographic-semantic processes (Harm & Seidenberg, 2004; Plaut & Gonnerman, 2000; Yang et al., 2009). Second, statistical regularities shape the representations that readers acquire as they learn to read, determining both the grain size and the similarity structure of those representations (Ziegler & Goswami, 2005, 2006). The present study, which contrasts two languages with very different sets of regularities, allows us not only to look at how languages diverge, but also at how L2 acquisition is affected by these regularities.

From a neurobiological perspective, numerous studies suggest that for all languages, word reading depends on connectivity and organization of a network of (primarily left hemisphere) sites (e.g., Pugh et al., 2000, 2013). Functional neuroimaging studies suggest that the structure of this network is largely universal, representing a cross-linguistic functional organization for word reading (see Carreiras, Armstrong, Perea, & Frost, 2014; Dehaene, Cohen, Morais, & Kolinsky, 2015 for review and discussion), although differences in relative weighting of circuits may occur due to differences in the statistical structure of the writing systems. Neuroimaging studies of reading acquisition in typically developing learners indicate that skilled visual word reading in L1 thus involves temporoparietal (TP), occipito-temporal (OT), frontal, and sub-cortical components (Pugh et al., 2010; Schlaggar & McCandliss, 2007). The TP component includes the angular gyrus and supramarginal gyrus in the inferior parietal lobule (IPL), and the posterior aspect of the superior temporal gyrus (STG; Wernicke's area). Developmental imaging studies also indicate that as word reading becomes more fluent there is a relative shift in activation, with increases in the automatic, skilled pathways in left-hemisphere (LH) ventral occipito-temporal cortex, including the so-called Visual Word Form Area (Dehaene, Le Clec'h, Poline, Le Bihan, & Cohen, 2002). Recently, Preston and colleagues (Preston et al., 2015) have shown that the extent of convergence in the activation associated with the processing of print and speech in L1 in eight year olds is a predictor of the development of reading abilities two years later. Thus, successful reading acquisition for L1 depends on reorganization of oral language networks in the brain into amodal reading related systems (see also Shankwiler et al., 2008; Frost et al., 2009). Our most recent work (Rueckl et al., 2015) indicates that this left hemisphere (LH) reorganization is a hallmark of fluent reading across four highly contrastive languages (English, Hebrew, Chinese, and Spanish), including the two examined here. This depiction of the neural basis of skilled L1 reading appears to be relatively clear at this point and can serve as a foundation for new studies of L2 literacy learning.

Given the largely invariant LH organization, the question of how second language circuits are incorporated, and how this might vary depending on the relative division of labour across languages is interesting (Bolger, Perfetti, & Schneider, 2005; Perfetti et al., 2007). The mechanism by which this functional reading network responds to the acquisition of a second writing system has been recently described in terms of two distinct processes, *accommodation* and *assimilation* (Liu, Dunlap, Fiez, & Perfetti, 2007; Perfetti et al., 2007). Accommodation refers to the divergence of the functional networks utilised in processing the two languages, with new procedures being utilised to process L2. In contrast, assimilation refers to functional convergence, where the existing L1 reading network is utilised for the L2 processing. Importantly, different L1 and L2 pairs may show different patterns of accommodation and assimilation, depending on: 1) the similarity or dissimilarity of the L1 and L2, 2) variability in L1 reading experience and

automaticity, 3) individual differences in statistical learning (SL) abilities, and 4) interactions among these factors (Mei et al., 2015; Nelson, Liu, Fiez, & Perfetti, 2009). For example, Das, Padakannaya, Pugh, and Singh (2011) examined Hindi-English biliterate adults who either learned both orthographies together in first grade (simultaneous) or five years apart (sequential). We found that sequential L2 learners were prone to use L1 Hindi circuits for L2 English (suggesting assimilation), while simultaneous learners showed differences in dorsal/ventral weighting of LH activation (suggesting some degree of accommodation). Moreover, computational accounts (and informed speculation) might suggest that even for the same two languages the direction of learning (which is L1 or L2) could moderate the contributions of assimilation or accommodation, and we examine this in the current study.

In the present study, we aimed to investigate the neurobiological underpinning of acquiring literacy in L2 when literacy in L1 has been established and stabilised. Our overarching goal was to address three critical theoretical questions. First, how does L1 knowledge affect the learning of L2 given their contrasting structural properties? Second, what are the salient neurobiological markers of acquiring literacy in an L2? And third, what are the consequences of learning the structural properties of an L2 on the processing of L1 in terms of neural changes? In order to probe these complex issues, our study tracked parallel cohorts of English L1 learners of Hebrew L2, and Hebrew L1 learners of English L2, for a period of 2 years. Participants received a battery of linguistic and general cognitive measures at three time points - upon entry to the study, after one year, and after two years. Participants also received in a functional magnetic resonance imaging (fMRI) session upon entry to the study and after two years, in which they performed a semantic judgement test on printed and auditory words and pseudowords in both their L1 and L2. This provided measures of the processing of both languages in both auditory and visual modalities.

Because the study is still in progress, the present paper focuses on the initial findings of the first epoch (Ep1, encompassing the fMRI and behavioural data collected upon entry to the study). The primary results of interest from Ep1 relate to the differences and similarities in processing L1 and L2, given the extensive differences between the Hebrew and the English orthographic, morphological and phonological systems. Because convergence of print and speech processing neurocircuitry has been shown to be a marker of reading ability in L1 (Preston et al., 2015) and convergence of L1 and L2 reading neurocircuitry has been shown to be a marker of L2 reading proficiency (Cao, Tao, Liu, Perfetti, & Booth, 2013), our study focused then on these two main measures. Here we present data on differences in L1 and L2 processing, for both Hebrew and English native speakers learning a second language, while immersed in the foreign linguistic environment. It should be noted that all participants had achieved at least a basic level of proficiency in their relevant L2 at the start of the study, allowing us to test for L2 proficiency and examine the processing of L2 stimuli. For both languages we assessed the extent of convergence of print and speech processing neurocircuitry in L1 and L2 (our marker for initial reading proficiency in L1 vs. L2), and the extent of convergence of L1 and L2 print processing (our marker of initial assimilation and accommodation of L2 writing system).

2. Methods

2.1. Participants and overall design

46 native American-English speakers (31 females, mean age 23.2) and 56 native Hebrew speakers (18 females, mean age 22.2) participated in the study. The native English speakers (EL1 cohort) all were recruited in Jerusalem, Israel, and all were participating in a Hebrew language course and/or working or studying in Hebrew at the start of the study. The native Hebrew speakers (HL1 cohort) were recruited in New York and were all working and/or studying in English. All participants reported either normal or corrected-to-normal vision, and no diagnosis of dyslexia or dysgraphia. Informed written consent was obtained from all participants before participation. The study was approved by the IRBs of Yale University and The Hebrew University of Jerusalem.

Participants were recruited separately at the two sites, and participated in six sessions, divided into three epochs, Ep1 at the beginning of the first year, Ep2 at the beginning of the second year, and Ep3 at the conclusion of the second year. Ep1 comprised 3 sessions in total, two behavioural sessions covering a battery of measures of L1 and L2 ability, as well as a number of general cognitive measures, and the first fMRI session. In the present paper we present the fMRI data from Ep1 only, and its relation to the Multi-lingual Naming Test (MINT; Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2008). This behavioural measure was selected as a cross-linguistically comparable measure of proficiency, as it utilises identical pictorial stimuli for both languages, with comparable word frequencies across the different languages.

A word of caution: Certain differences in cohorts were naturally expected in extent of initial proficiency in L2. Whereas English is taught in schools in Israel, and English language content is common, the reverse is not necessarily true (albeit most English L1 participants had some exposure to Hebrew script given their Jewish background). None of the HL1 cohort, however, reported use of English at home, and all of them self-reported having Hebrew as a single mother tongue. We should note that for the overarching goal of the study, this was not a major concern because each participant serves as their own control, providing measures of their improvement in L2 over time. We will address the impact of this issue in reference to Ep1 measures in the final discussion.

Data from seven subjects in the HL1 cohort were removed from all analyses, due to being diagnosed with attentional disorders or to being left-handed.

2.2. fMRI task

An event-related design was used for functional scanning with 3 crossed variables: Language (English, Hebrew) by Modality (print, speech) by Stimulus Type (living, non-living, pseudoword) for a total of 12 stimulus conditions. Subjects saw and heard printed and spoken isolated single words and pronounceable pseudowords in both English and Hebrew, and responded to each with a

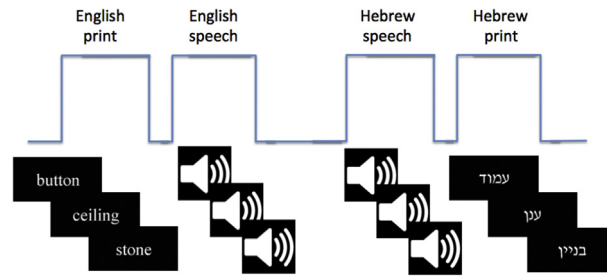


Fig. 1. In scanner task design.

yes/no button press as to whether it referred to a living thing. The semantic judgement task was chosen to ensure full lexical access to the stimuli. Subjects were instructed to respond “no” (i.e., non-living) to pseudowords, and received practice training before being scanned. In each of 10 functional imaging runs, event types were segregated into 4 1-min long blocks: 1) spoken English stimuli, 2) printed English stimuli, 3) spoken Hebrew stimuli, and 4) printed Hebrew stimuli. Each block contained both real and pseudowords. Block order was pseudorandomized across runs: in each run, the first two blocks were either both in English, or both in Hebrew; the last two blocks were from the other language. A 16-s washout period was inserted in the middle of the run to separate the language blocks with a fixation point shown for the final 3 s to alert the participant that a new set of stimuli was about to begin. This was intended to encourage subjects to stay in a language-specific mode for longer periods of time, and to minimize language switching. Across the 10 runs, 40 trials were obtained in each of the 8 “non-living” and “pseudoword conditions; 20 trials were obtained in each of the 4 “living” conditions, for a total of 400 trials. See Fig. 1.

2.3. MRI data acquisition

Data for the HL1 cohort were collected at the New York University Center for Brain Imaging (NYU-CBI) in New York City, USA, using a Siemens Allegra 3T MRI system (Siemens AG, Erlangen, Germany) and 12-channel head coil. Data for the English cohort were collected at the Hebrew University, Jerusalem, Israel, at either the Ein Kerem University Hospital campus (26 subjects) or the Givat Ram campus (20 subjects) of the Hebrew University, using a Siemens 3T MRI system (Skyra in Givat Ram, and Trio in Ein Kerem) and 12-channel head coil.

Participants were situated supine in the scanner, given noise-reducing earplugs and headphones, and additional foam wedges to minimize movement. Prior to functional imaging, sagittal localizers were prescribed (matrix size = 240×256 ; voxel size = $1 \times 1 \times 4$ mm; FoV = 240/256 mm; TR = 20 ms; TE = 6.83 ms; flip angle = 25°). Next, anatomical scans were acquired for each participant in an axial-oblique orientation parallel to the intercommissural line (MPRAGE; matrix size = 256×256 ; voxel size = $1 \times 1 \times 1$ mm; FoV = 256 mm; TR = 2530 ms; TE = 3.66 ms; flip angle = 7°). Following this, T2*-weighted functional images were then collected in the same orientation as the anatomical volumes (32 slices; 4 mm slice thickness; no gap) using single-shot echo planar imaging (matrix size = 64×64 ; voxel size = $3.4375 \times 3.4375 \times 4$ mm; FoV = 220 mm; TR = 2000 ms; TE = 30 ms; flip angle = 80°).

During functional scans, trials were presented at pseudo-random intervals, with inter-trial onset times jittered between 4 and 7 s. Occasional (10%) null trials were included to increase sensitivity, implemented as longer ITIs of 10–13s (Friston, Zarahn, Josephs, Henson, & Dale, 1999). Ten functional runs were acquired, each 4:24 long, with 132 full-brain images each. The first six volumes within each run were discarded to allow for stabilization of the magnetic field.

2.4. Image preprocessing and statistical analysis

Data were analysed using AFNI (Cox, 1996). Functional images were pre-processed by first correcting for slice acquisition time. Following this, functional images were coregistered with anatomical images, corrected for motion using a six-parameter rigid-body transform, and normalized to the Colin27 brain in Talairach space using a non-linear transform. These three steps were combined into a single applied transform and the data were resampled to a 3 mm isotropic voxel size. Finally, all images were smoothed to the same final 8 mm smoothness level (see below).

At the subject level, data were submitted to a multiple regression analysis with nuisance regressors representing a) run-to-run mean differences; b) first- and second-order temporal drift within each run; and c) the six movement parameters. The standard BOLD hemodynamic response function model was used as the regressor for trial events, resulting in 12 beta-weight maps from each subject, one for each stimulus condition. Next, these subject beta maps were used in a multivariate model to examine effects of subject group, stimulus conditions, and their interactions (3dMVM, Chen, Adelman, Saad, Liebenluft, & Cox, 2014). To control for cross-scanner differences, we implemented the procedures recommended by the fBIRN consortium (Glover et al., 2012) as follows. First, data from each subject were smoothed to the same final smoothness level of 8 mm using an iterative procedure. Second, images were scaled to percent-signal change values. Third, for each subject, we computed a voxelwise signal-to-fluctuation-noise-ratio (SFNR) map, and this estimate of temporal noise was used as a nuisance covariate in the voxel-wise, across-subject activation analysis.

Resulting groupwise statistical maps were thresholded at a voxelwise threshold of $p = .001$. To control for family-wise error rates,

Table 1

Average accuracy and SD in Hebrew and English MINT for English L1 (EL1) and Hebrew L1 (HL1) cohorts.

Cohort		MINT English	MINT Hebrew
EL1	Accuracy	0.979	0.606
	SD	0.037	0.178
HL1	Accuracy	0.758	0.959
	SD	0.126	0.043

Monte Carlo simulations were performed (3dClustSim; 10,000 iterations) using all brain voxels within the TT_N27 template brain, and using the spherical autocorrelation function parameters concerning the error time series (performed in response to the latest recommendations regarding cluster correction in fMRI research; Eklund, Nichols, & Knutsson, 2016). The minimum cluster threshold for a corrected alpha level of $p = .05$ was 25 voxels (3 mm isotropic).

For analysis of overlap, a series of anatomical ROIs were utilised. A canonical reading network was defined using a series of ROIs based on previous literature (Preston et al., 2015; Pugh et al., 2010; 2013). Four primary ROIs in each hemisphere were anatomically defined using atlas-defined regions from the CA_N27_ML atlas included in afni. The network comprised of the bilateral IFG (divided into pars orbitalis, triangularis and opercularis), superior temporal gyrus (STG), inferior parietal cortex (IPC), and the fusiform gyrus (FFG).

3. Results

3.1. Behavioural results

The primary measure of language and vocabulary skills in L1 and L2 as reported in this paper is the MINT. This test is a picture naming test suited for cross-linguistic comparison, developed in order to compare vocabulary in English, Spanish, Hebrew and Chinese. The same battery of pictures was used to measure both languages, allowing for a direct comparison of the results across languages and across cohorts. The two cohorts showed similar proficiency at their L1, and their scores were virtually at ceiling in their native language. However, as expected, the native Hebrew speakers were more proficient in English than the native English speakers were in Hebrew. A two-way analysis of variance of the effect of cohort and language on accuracy thus showed a significant effect of cohort ($F(1,97) = 29.528$, $p < .001$), language ($F(1,97) = 14.802$, $p < .001$), and a significant interaction between the two ($F(1,97) = 346.507$, $p < .001$) (see Table 1).

The accuracy in the in-scanner task was high across all conditions (see Table 2), with a significant effect of language ($F(1,98) = 4.488$, $p < .05$, Eng > Heb), and a language by cohort interaction ($F(1, 98) = 13.369$, $p < .001$) such that for each cohort accuracy was higher for L1. So here, too, we can see higher L2 proficiency for the HL1 cohort.

3.2. Groupwise L1/L2 activation differences

Primary group contrasts of L1 and L2 word-reading processes (excluding pseudowords, and collapsing across animate and inanimate stimuli, see Fig. 2) were conducted across the whole group, and across each cohort individually. The contrast of neural activity during word reading between L2 and L1 processing across the whole group showed greater activation for L2 ($L2 > L1$) in the left inferior frontal gyrus (IFG), spreading into the middle frontal gyrus (MFG) and precentral gyrus (PCG). Greater activation for L1 ($L1 > L2$) was seen in the bilateral superior temporal gyri (STG), spreading into the inferior parietal lobule (IPL) and middle temporal gyrus (MTG) in the right hemisphere, as well as the right anterior cingulate cortex (ACC). As expected from the differences in L2 proficiency, greater effects were seen in the EL1 cohort, who showed all effects seen in the whole group analysis, with an additional L1 preference in the bilateral IPL and left SMG. The HL1 cohort showed an L1 preference in bilateral IPL.

In posterior regions, L1 and L2 differences showed an interaction with cohort, with a bilateral medial preference for English in the cuneus and lingual gyri, and a lateral preference for Hebrew in the inferior occipital and fusiform gyri. A second order contrast of the differences in L2-L1 processing between the two cohorts showed this to be a significant effect. See Table 3 for a list of all significant clusters.

Table 2

Average accuracy and SD in Hebrew and English for word stimuli in the in-scanner task (collapsed across modality), for English L1 (EL1) and Hebrew L1 (HL1) cohorts.

Cohort		English	Hebrew
EL1	Accuracy	0.946	0.922
	SD	0.011	0.013
HL1	Accuracy	0.952	0.958
	SD	0.011	0.012

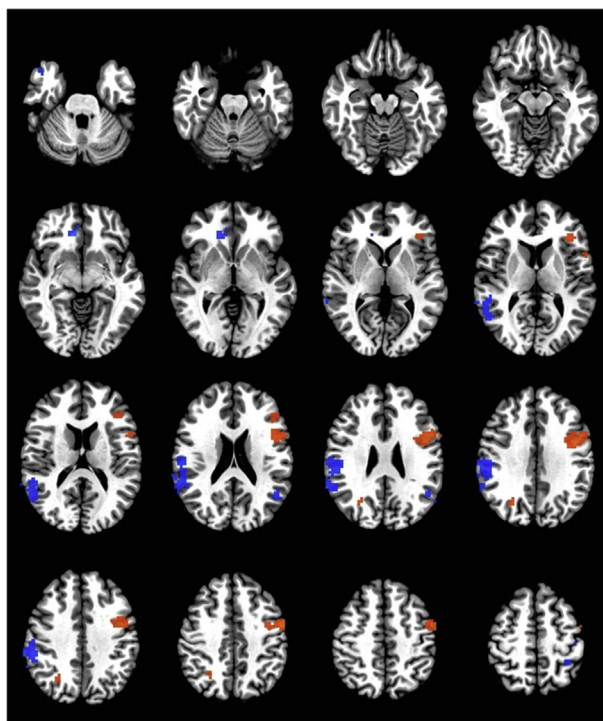


Fig. 2. L2-L1 activation. L2 > L1 in red, L1 > L2 in blue, left hemisphere on right. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Clusters showing main effect of Language (L2-L1), $p = .001$, cluster corrected at $p = .05$.

L/R	Region	Extent (Voxels) ^a	Peak voxel (Talairach Coordinates)			Center of mass (Talairach Coordinates)			Effect
			x	y	z	x	y	z	
L	Inferior Frontal, and PreCentral Gyri	226	−52.5	+1.5	+44.5	−44.4	−2.4	+31.4	L2 > L1
L	Inferior Frontal, and Medial Frontal Gyri.	58	−49.5	−31.5	+17.5	−39.9	−29.2	+14.2	L2 > L1
R	PreCuneus	30	+25.5	+58.5	+41.5	+26.0	+58.9	+34.5	L2 > L1
R	Inferior Parietal Lobule, Superior Medial, and PostCentral Gyri	325	+61.5	+34.5	+35.5	+55.5	+35.9	+23.6	L1 > L2
R	Superior Temporal Gyrus	37	+43.5	−19.5	−33.5	+42.7	−13.3	−31.1	L1 > L2
R	Anterior Cingulate Cortex	34	+7.5	−31.5	−6.5	+8.7	−33.7	−3.6	L1 > L2
L	Inferior Parietal Lobule	33	−40.5	+31.5	+59.5	−34.1	+39.0	+55.8	L1 > L2
L	Superior Temporal Gyrus	32	−52.5	+64.5	+23.5	−46.3	+55.7	+22.9	L1 > L2
L	PreCentral Gyrus	30	−37.5	+25.5	+62.5	−33.8	+16.7	+59.1	L1 > L2

^a Voxels are $3 \times 3 \times 3$ mm, or 27 mm^3 , in size.

3.3. Identifying assimilation of L1 and L2 activation for print and speech tokens in regions of interest (ROIs)

A probabilistic map of joint activation in two print word conditions was created for each subject, controlling for individual overall level of activation, by standardising each individual's t-value map for L1 and L2 and then converting these standardised scores into p-values. The voxel-wise product of the two p-value maps—constituting the joint probability of activation—which was then converted back into z-scores, provides a probabilistic measure of co-activation while reading words in L1 and in L2, with high measure of joint probability pointing to greater overlap—or assimilation, and low measure of joint probability suggesting accommodation. Previous literature has utilised a binary measure of convergence (Cao et al., 2013; Preston et al., 2015), however a probabilistic measure, as we use here, should better be able to model the non-binary nature of the processing.

The average score within each ROI was extracted for each subject. ANCOVA analyses were conducted for each ROI, with hemisphere (LH vs. RH) and modality (print vs. speech) as within-subject factors, and cohort (EL1 vs. HL1) as the between-subject factor. MINT L2 score was a covariate in this analysis (note that this controls for the potential confound of cohort differences in L2 ability as we examine the other factors and their interactions; where significant we can interpret this as effects of individual differences in L2 vocabulary/proficiency).

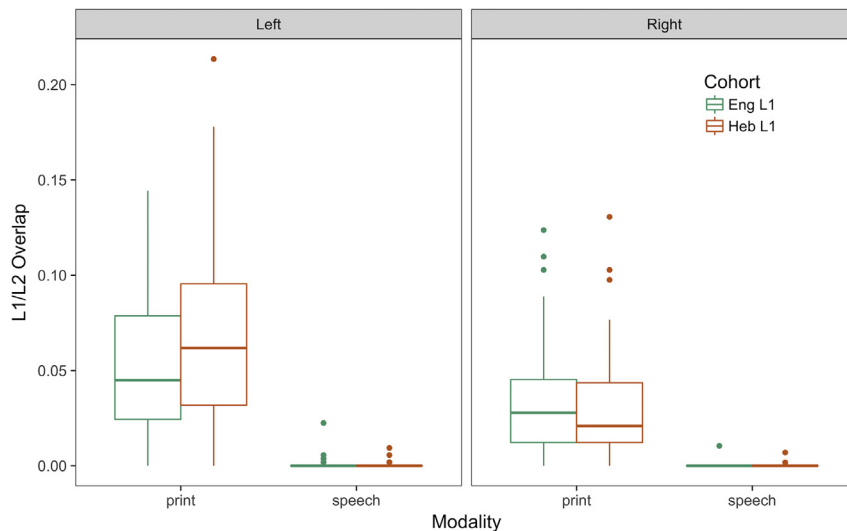


Fig. 3. L1/L2 overlap in FFG.

In the IFG pars opercularis (IFG-opc) main effects were found for L1/L2 overlap by modality ($F(1,94) = 4.307$, $p < .05$) with higher overlap for print than for speech. In the IFG pars triangularis (IFG-tri), a main effect of hemisphere ($F(1,94) = 5.928$, $p < .05$) showed greater left hemisphere (LH) than right hemisphere (RH) overlap, with a marginally significant interaction between hemisphere and modality ($F(1,94) = 2.794$, $p = .098$) showing greater overlap for speech than for print in LH. In the IFG pars orbitalis (IFG-orb) a hemisphere by cohort interaction ($F(1,94) = 4.166$, $p < .05$) revealed heightened left lateralisation of L1/L2 co-activation in the EL1 cohort, while a further modality by cohort interaction ($F(1,94) = 6.995$, $p = .010$) showed heightened overlap for speech over print to a greater extent for the HL1 cohort. In the STG, the only significant effect was greater general L1/L2 co-activation for speech than for print ($F(1,94) = 48.107$, $p < .001$). In the IPC, a main effect of hemisphere ($F(1,94) = 4.033$, $p < .05$) reflected greater LH than RH L1/L2 co-activation for both modalities in parietal cortex. Finally, the FFG showed a main effect of hemisphere ($F(1,94) = 4.776$, $p < .05$; LH > RH) and modality ($F(1,94) = 8.476$, $p < .01$; print > speech). A further complex three-way interaction between hemisphere, modality and cohort ($F(1,94) = 5.538$, $p < .05$), as seen in Fig. 3, indicated that a general LH increase of co-activation seen for print relative to speech was further qualified by L2 proficiency, such that if L2 was English, this increase was stronger than if the L2 was Hebrew. As this was not qualified by L2 scores this seems to be a complex language modifier on how FFG reorganizes for new print coding (see discussion).

3.4. Identifying print-speech convergence within L1 or L2 in ROIs

In the same manner as the analysis of L1/L2 co-activation, maps were created for a probabilistic measure of co-activation between print and speech within each language. Because our previous work in L1 (Preston et al., 2015; Rueckl et al., 2015) indicates that this integration is both highly related to skill and is to some degree invariant across languages, how this plays out in L2 learning is of substantial interest. The same ANCOVA analysis framework was employed as before, but the modality variable is here replaced with language (i.e., we measure print/speech co-activation for English vs. Hebrew). The full model again allows us to examine hemisphere by language by cohort interactions as well as to control for MINT L2 performance differences. In all three divisions of IFG a complex three-way interaction between hemisphere, language, and Cohort was obtained (all F 's > 14, p 's $\leq .001$) and as seen in Fig. 4, LH integration of print and speech is always greater for the L2 than the L1 whereas the RH shows almost no difference. In the STG, no effects are found.

Strikingly, relative to IFG, a complex three-way interaction is also seen in the IPC ($F(1,94) = 4.021$, $p < .05$), but in the opposite direction with respect to L1 and L2. As seen in Fig. 5, in LH IPC print/speech convergence is greater for the L1 than the new L2. Thus, posterior cortex shows a prominence for the old language, while IFG, arguably the active working system, shows print/speech prominence for the new language. Although this difference is seen more strongly in the EL1 cohort, this is expected given the greater L2 proficiency and earlier exposure to the L2 orthography in the HL1 cohort. It should be noted that although a difference between L1 and L2 in the HL1 cohort is not visible in Fig. 5, a post-hoc t -test shows marginally significantly greater overlap for L1 than L2 ($t(52) = 1.437$, $p = .078$).

In FFG no significant main effects or interactions were found, however an interaction between hemisphere and language was marginally qualified by MINT L2 ($F(1,94) = 3.091$, $p = .082$), with greater L2 print/speech convergence in LH related to greater L2 proficiency.

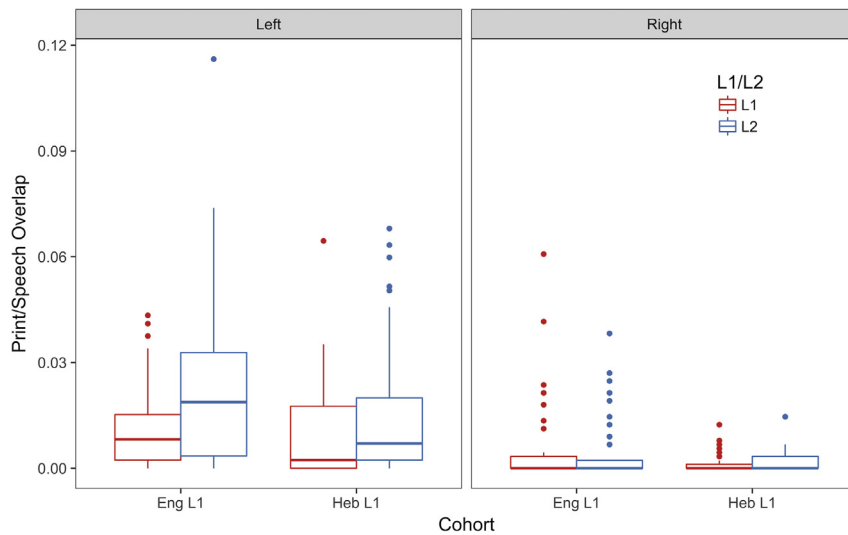


Fig. 4. Print/speech overlap across whole IFG.

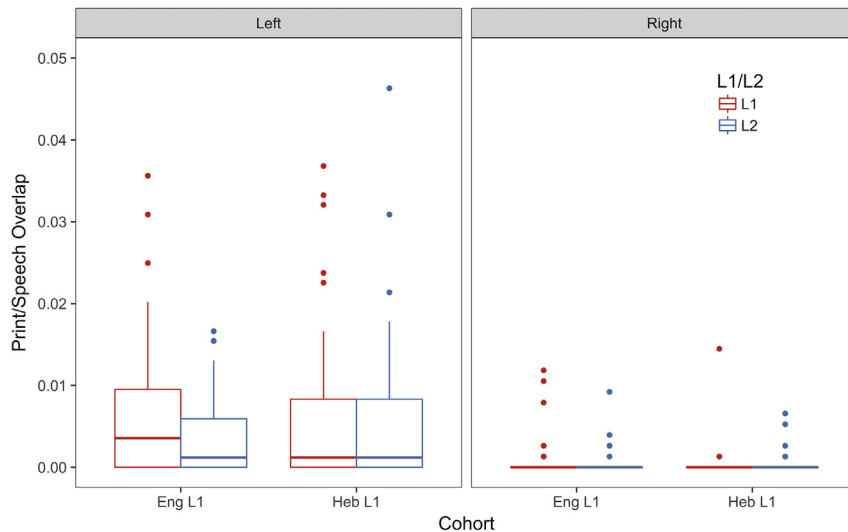


Fig. 5. Print/speech overlap in the IPC.

4. Discussion

The primary groupwise contrasts show, as expected, that L2 reading processing incurs a greater activation than L1 across canonical reading areas in the left hemisphere and some of their right hemisphere homologues. However, L1 reading did show greater activation in a number of (primarily right hemisphere) parieto-occipital regions of the reading network, typically tied to skilled and automatic mapping processes in reading (Pugh et al., 2010). The medial preference for English vs. lateral preference for Hebrew in posterior regions may be driven by differences in featural characteristics of the two orthographic systems, Hebrew and Roman, or possibly by differences in stimuli sets, although the stimuli in each language were to some extent equated for frequency. There has been limited study of the neurological differences between reading Hebrew and English (Bick et al., 2011; Rueckl et al., 2015), and none that have a direct comparison as in the task reported here. Bick et al. (2011) did find some differences in the posterior regions associated with morphological processing during word reading, and given the inherent added morphological complexity in Hebrew it is possible that this played a role. However, in absence of any strong a-priori hypotheses regarding such a difference, further study is necessary to draw any strong conclusions.

The measure of overlap of L1 and L2 in both print and speech showed overall greater assimilation in the left hemisphere than in the right, across all areas of the canonical reading network. The FFG, which incorporates the VWFA and which has been shown to be specifically related to orthographic processing, mostly showed an effect of convergence in print. The greater effect for the Hebrew L1 cohort is likely driven by the greater and earlier L2 exposure, with the orthographic system being learned at an earlier maturational

stage, as the sensitivity of the FFG has been shown to be critically related to the acquisition of skilled reading (Booth et al., 2001). This should lead to more automaticity in reading processes, and greater integration of the statistical properties and mapping of the L2 orthography into the reading network. However, it may also speak to differences in the statistical regularities of each of the two orthographies, which raises the question of how this might play out in other contrastive L1/L2 dyads.

These results show that overall, similar networks of processing are utilised in L1 and L2 regardless of language direction. We focused in this paper on L1/L2 overlap (for print or for speech) to test the assimilation hypothesis, and in general we find that critical reading networks, especially the VWFA, a region associated with skill, automaticity, and fast processing of print (Booth et al., 2001; Pugh et al., 2013) seem to be co-opted in both cohorts by L2 learning, despite the form differences between the two alphabets. It is important to note that assimilation of L2 reading into existing L1 networks does not entail that similar computations are being performed, or that the L1 processes are being utilised to process the L2. We take assimilation of L2 rather to be a mark of the incorporation of new regularities into the existing system, rather than the creation of new systems.

The most interesting results are of the print and speech convergence in each language. Previous research has shown that print-speech integration is predictive of reading proficiency in L1 readers (Preston et al., 2015), and has also shown relative invariance to cross-linguistic differences (Rueckl et al., 2015). The present study extends these results to the L2 domain, and shows interesting differences between different regions of the reading network. Posterior regions of the reading network show more print-speech integration for L1 than L2, while the IFG, arguably the more active and less automatic system, being more heavily activated by the processing of less frequent and inconsistent stimuli (Pugh et al., 2000, 2010), conversely shows greater integration for L2. This suggests that integration in posterior regions is driven primarily by automatic processes of skilled reading that take experience to develop (Booth et al., 2004), whereas the IFG, in addition to being less print-specific, is an active workspace that reflects more effortful language processing, thereby incurring greater activation for L2 than L1 (as indeed is shown by the brain activation maps).

Although marginal in significance, qualification by the L2 MINT scores suggests that print-speech integration in the FFG is somewhat dependent on proficiency, with greater integration appearing as L2 proficiency and exposure increase. It is also worth noting that this result is novel evidence of amodal processes in ventral pathway for reading, typically seen as a region dedicated to purely visual orthographic processing (Cohen & Dehaene, 2004; Dehaene & Cohen, 2011). However it is possible, given that our ROI is anatomically rather than functionally defined, that this effect is partly driven by left inferior-temporal regions that have been shown to be sensitive to multi-modal lexical representations (Cohen, Jobert, Le Bihan, & Dehaene, 2004; Zhao et al., 2017). Work by Zhao et al. (2017) has also suggested that more anterior regions of the FFG encode abstract phonological information, with increasing phonological involvement along an anterior-posterior axis. In any case, the current results suggest that the encoding of phonological information in the FFG develops as language proficiency increases, and as the mappings between phonology and orthography are learned and incorporated into the broader language network, and challenges a simple feed-forward view of the role of the fusiform in reading.

These results are backed up by the primary groupwise findings, and together these results provide a clear picture of the shift in reading circuitry as readers achieve proficiency. Posterior occipito-temporal regions, including the VWFA, come into play more for skilled readers, as the statistical regularities in orthographic mappings are integrated into the network. Less skilled reading pulls in wider networks of active effortful process, encompassing frontal, parietal and temporal regions of the reading network that necessitate fine-grained articulatory coding.

It is important to emphasise that these are preliminary results, focusing on group differences. It thus remains to be seen which long term changes will be revealed both at the group and the individual level, which neural and behavioural characteristics will be markers of achieving fluency, and how the relation between the various effects reported here will result in long term changes in the language network in general and the reading network in particular.

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References

- August, D., & Shanahan, T. (2006). *Developing literacy in second-language learners: Report of the national literacy panel on language-minority children and youth*. Mahwah, NJ: Erlbaum.
- Bialystok, E., & Miller, B. (1999). The problem of age in second-language acquisition: Influences from language, structure, and task. *Bilingualism: Language and Cognition*, 2(2), 127–145. <http://doi.org/10.1017/S0016774600023726>.
- Bick, A. S., Goelman, G., & Frost, R. (2011). Hebrew brain vs. English brain: Language modulates the way it is processed. *Journal of Cognitive Neuroscience*, 23(9), 2280–2290. <http://doi.org/10.1162/jocn.2010.21583>.
- Bolger, D. J., Perfetti, C. A., & Schneider, W. (2005). Cross-cultural effect on the brain revisited: Universal structures plus writing system variation. *Human Brain Mapping*, 25(1), 92–104. <http://doi.org/10.1002/hbm.20124>.

- Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (2004). Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience*, 16(7), 1234–1249. <http://doi.org/10.1162/0898929041920496>.
- Booth, J. R., Burman, D. D., Van Santen, F. W., Harasaki, Y., Gitelman, D. R., et al. (2001). The development of specialized brain systems in reading and oral-language. *Child Neuropsychology*, 7(3), 119–141. <http://doi.org/10.1076/chin.7.3.119.8740>.
- Cao, F., Tao, R., Liu, L., Perfetti, C. A., & Booth, J. R. (2013). High proficiency in a second language is characterized by greater involvement of the first language Network: Evidence from Chinese learners of English. *Journal of Cognitive Neuroscience*, 25(10), 1649–1663. <http://doi.org/10.1162/jocn>.
- Carreiras, M., Armstrong, B. C., Perea, M., & Frost, R. (2014). The what, when, where, and how of visual word recognition. *Trends in Cognitive Sciences*, 18, 90–98. <http://doi.org/10.1016/j.tics.2013.11.005>.
- Chen, G., Adelman, N. E., Saad, Z. S., Liebenluft, E., & Cox, R. W. (2014). Applications of multivariate modeling to neuroimaging group analysis: A comprehensive alternative to univariate general linear model. *NeuroImage*, 99, 571–588. <http://doi.org/10.1038/jid.2014.371>.
- Cohen, L., & Dehaene, S. (2004). Specialization within the ventral stream: The case for the visual word form area. *NeuroImage*, 22(1), 466–476. <http://doi.org/10.1016/j.neuroimage.2003.12.049>.
- Cohen, L., Jobert, A., Le Bihan, D., & Dehaene, S. (2004). Distinct unimodal and multimodal regions for word processing in the left temporal cortex. *NeuroImage*, 23(4), 1256–1270. <http://doi.org/10.1016/j.neuroimage.2004.07.052>.
- Cox, R. W. (1996). AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research*, 29, 162–173. <http://doi.org/10.1006/cbmr.1996.0014>.
- Das, T., Padakannaya, P., Pugh, K. R., & Singh, N. C. (2011). Neuroimaging reveals dual routes to reading in simultaneous proficient readers of two orthographies. *NeuroImage*, 54(2), 1476–1487. <http://doi.org/10.1016/j.neuroimage.2010.09.022>.
- Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences*, 15(6), 254–262. <http://doi.org/10.1016/j.tics.2011.04.003>.
- Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: Behavioural and cerebral changes induced by reading acquisition. *Nature Reviews Neuroscience*, 16(4), 234–244. <http://doi.org/10.1038/nrn3924>.
- Dehaene, S., Le Clec'h, G., Poline, J.-B., Le Bihan, D., & Cohen, L. (2002). The visual word form area: A prelexical representation of visual words in the fusiform gyrus. *NeuroReport*, 13(3), 321–325. <http://doi.org/10.1097/00001756-200203040-00015>.
- DeKeyser, R. M. (2000). The robustness of critical period effects in second language acquisition. *Ssla*, 22, 499–533. <http://doi.org/0272-2631/00>.
- Eklund, A., Nichols, T. E., & Knutson, H. (2016). Cluster failure: Why fMRI inferences for spatial extent have inflated false-positive rates. *Proceedings of the National Academy of Sciences*, 113(33), 201602413. <http://doi.org/10.1073/pnas.1602413113>.
- Friston, K. J., Zarahn, E., Josephs, O., Henson, R. N., & Dale, A. M. (1999). Stochastic designs in event-related fMRI. *NeuroImage*, 10(5), 607–619. <http://doi.org/10.1006/nimg.1999.0498>.
- Frost, R. (2011). Reading in Hebrew versus reading in English: Is there a qualitative difference? In K. R. Pugh, & P. McCauley (Eds.), *How children learn to read: Current issues and new directions in the integration of cognition, neurobiology and genetics of reading and dyslexia research and practice* (pp. 235–250). Taylor & Francis.
- Frost, R., Kugler, T., Deutsch, A., & Forster, K. I. (2005). Orthographic structure versus morphological structure: Principles of lexical organization in a given language. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 31(6), 1293–1326.
- Frost, S. J., Sandak, R., Mencl, W. E., Landi, N., Rueckl, J. G., Katz, L., et al. (2009). Mapping the word reading circuitry in skilled and disabled readers. *How children learn to read: Current issues and new directions in the integration of cognition, neurobiology and genetics of reading and dyslexia research and practice* (pp. 3–19).
- Glover, G. H., Mueller, B. A., Turner, J. A., Van Erp, T. G. M., Liu, T. T., Greve, D. N., et al. (2012). Function biomedical informatics research network recommendations for prospective multicenter functional MRI studies. *Journal of Magnetic Resonance Imaging*, 36(1), 39–54. <http://doi.org/10.1002/jmri.23572>.
- Gollan, T. H., Weissberger, G. H., Runqvist, E., Montoya, R. I., & Cera, C. M. (2008). Self-rating of spoken language dominance: A multi-lingual naming test (MINT) and preliminary norms for young and aging Spanish-English bilinguals. *Biling*, 6(9), 2166–2171. <http://doi.org/10.1021/nl061786n.Core-Shell>.
- Harm, M. W., & Seidenberg, M. S. (2004). Computing the meanings of words in Reading: Cooperative division of labor between visual and phonological processes. *Psychological Review*, 111(3), 662–720. <http://doi.org/10.1037/0033-295X.111.3.662>.
- Johnson, J. S., & Newport, E. L. (1989). Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. *Cognitive Psychology*, 21, 60–99. [http://doi.org/https://doi.org/10.1016/0010-0285\(89\)90003-0](http://doi.org/https://doi.org/10.1016/0010-0285(89)90003-0).
- Lerner, I., Armstrong, B. C., & Frost, R. (2014). What can we learn from learning models about sensitivity to letter-order in visual word recognition? *Journal of Memory and Language*, 77(C), 40–58. <http://doi.org/10.1016/j.jml.2014.09.002>.
- Liu, Y., Dunlap, S., Fiez, J., & Perfetti, C. A. (2007). Evidence for neural accommodation to a writing system following learning. *Human Brain Mapping*, 28(11), 1223–1234. <http://doi.org/10.1002/hbm.20356>.
- Mei, L., Xue, G., Lu, Z. L., Chen, C., Wei, M., He, Q., et al. (2015). Long-term experience with Chinese language shapes the fusiform asymmetry of English reading. *NeuroImage*, 110, 3–10. <http://doi.org/10.1016/j.neuroimage.2015.01.030>.
- Nelson, J. R., Liu, Y., Fiez, J., & Perfetti, C. A. (2009). Assimilation and accommodation patterns in ventral occipitotemporal cortex in learning a second writing system. *Human Brain Mapping*, 30(3), 810–820. <http://doi.org/10.1002/hbm.20551>.
- Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S. F., et al. (2000). A cultural effect on brain function. *Nature Neuroscience*, 3(1), 91–96. <http://doi.org/10.1038/71163>.
- Perfetti, C. A., Liu, Y., Fiez, J., Nelson, J. R., Bolger, D. J., & Tan, L.-H. (2007). Reading in two writing systems: Accommodation and assimilation of the brain's reading network. *Bilingualism: Language and Cognition*, 10(2), 131. <http://doi.org/10.1017/S1366728907002891>.
- Plaut, D. C., & Gonnerman, L. M. (2000). Are non-semantic morphological effects incompatible with a distributed connectionist approach to lexical processing? *Language & Cognitive Processes*, 15(4–5), 445–485. <http://doi.org/10.1080/01690960050119661>.
- Pollatsek, A., Treiman, R., & Frost, R. (2015). Cross-linguistic perspectives on letter-order processing. *The oxford handbook of reading* Oxford University Press <http://doi.org/10.1093/oxfordhb/9780199324576.013.9>.
- Preston, J. L., Molfese, P. J., Frost, S. J., Mencl, W. E., Fulbright, R. K., Hoeft, F., et al. (2015). Print-speech convergence predicts future reading outcomes in early readers. *Psychological Science*, 27(1) <http://doi.org/10.1177/0956797615611921>.
- Pugh, K. R., Frost, S. J., Sandak, R., Landi, N., Moore, D., Della Porta, G., et al. (2010). Mapping the word reading circuitry in skilled and disabled readers. In K. R. Pugh, & P. McCauley (Eds.), *The neurobasis of reading* (pp. 281–305). Oxford University Press. <http://doi.org/10.1093/acprof:oso/9780195300369.003.0011>.
- Pugh, K. R., Landi, N., Preston, J. L., Mencl, W. E., Austin, A. C., Sibely, D., et al. (2013). The relationship between phonological and auditory processing and brain organization in beginning readers. *Brain and Language*, 125(2), 173–183. <http://doi.org/10.1016/j.bandl.2012.04.004>.
- Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J.-R., et al. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities*, 6(2000), 207–213. [http://doi.org/10.1002/1098-2779\(2000\)6:3<207::AID-MRDD8>3.0.CO;2-P](http://doi.org/10.1002/1098-2779(2000)6:3<207::AID-MRDD8>3.0.CO;2-P).
- Rueckl, J. G., Paz-alonso, P. M., Molfese, P. J., Kuo, W., Bick, A. S., Frost, S. J., et al. (2015). A universal brain signature of proficient reading. *Proceedings of the National Academy of Sciences*, 112(50), 15510–15515.
- Schlaggar, B. L., & McCandliss, B. D. (2007). Development of neural systems for reading. *Annual Review of Neuroscience*, 30(1), 475–503. <http://doi.org/10.1146/annurev.neuro.28.061604.135645>.
- Shankweiler, D., Mencl, W. E., Braze, D., Tabor, W., Pugh, K. R., & Fulbright, R. K. (2008). Reading differences and brain: Cortical integration of speech and print in sentence processing varies with reader skill. *Developmental Neuropsychology*, 33(6), 745–775.
- Velan, H., & Frost, R. (2011). Words with and without internal structure: What determines the nature of orthographic and morphological processing? *Cognition*, 118(2), 141–156. <http://doi.org/10.1016/j.cognition.2010.11.013>.
- Yang, J., McCandliss, B. D., Shu, H., & Zevin, J. D. (2009). Simulating language-specific and language-general effects in a statistical learning model of Chinese reading. *Journal of Memory and Language*, 61(2), 238–257. <http://doi.org/10.1016/j.jml.2009.05.001.Simulating>.
- Zhao, L., Chen, C., Shao, L., Wang, Y., Xiao, X., Chen, C., et al. (2017). Orthographic and phonological representations in the fusiform cortex. *Cerebral Cortex*, 27(11), 5197–5210. <http://doi.org/10.1093/cercor/bhw300>.
- Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, 131(1), 3–29. <http://doi.org/10.1037/0033-2909.131.1.3>.
- Ziegler, J. C., & Goswami, U. (2006). Becoming literate in different languages: Similar problems, different solutions. *Developmental Science*, 9(5), 429–436. <http://doi.org/10.1111/j.1467-7687.2006.00509.x>.