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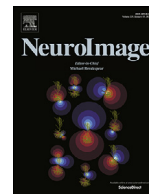
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## The brain signature of emerging reading in two contrasting languages

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### A B S T R A C T

Despite dissimilarities among scripts, a universal hallmark of literacy in skilled readers is the convergent brain activity for print and speech. Little is known, however, whether this differs as a function of grapheme to phoneme transparency in beginning readers. Here we compare speech and orthographic processing circuits in two contrasting languages, Polish and English, in 100 7-year-old children performing fMRI language localizer tasks. Results show limited language variation, with speech-print convergence evident mostly in left frontotemporal perisylvian regions. Correlational and intersect analyses revealed subtle differences in the strength of this coupling in several regions of interest. Specifically, speech-print convergence was higher for transparent Polish than opaque English in the right temporal area, associated with phonological processing. Conversely, speech-print convergence was higher for English than Polish in left fusiform, associated with visual word recognition. We conclude that speech-print convergence is a universal marker of reading even at the beginning of reading acquisition with minor variations that can be explained by the differences in grapheme to phoneme transparency. This finding at the earliest stages of reading acquisition conforms well with claims that reading exhibits a good deal of universality despite writing systems differences.

### 1. Introduction

Less than 6000 years ago writing systems began to develop to convey linguistic information through space and time. Despite dissimilarities among writing systems in regularity, frame and arrangement, they all represent the units of a spoken language. Irrespective of the writing system, reading depends on access to existing brain regions dedicated to the processing of spoken words. In consequence, the convergence of the speech and print processing systems onto a common neural network emerges as an invariant and universal signature of literacy proficiency (Rueckl et al., 2015) and one that is strongly associated with individual differences in reading outcomes (Preston et al., 2016). At the cognitive level, it is associated with bidirectional influences of one modality upon the other in behavior. Whether the orthography is transparent or opaque, logographic or alphabetic - perisylvian regions in inferior frontal (IFG) and superior and middle temporal (STG/MTG) gyri were consistently co-activated by both spoken and written words in adult readers of English, Spanish, Chinese and Hebrew (Rueckl et al., 2015). The authors argued that the invariance in speech-print convergence is the result of biological constraints imposed by perisylvian specialization for speech, and the need to use these specialized systems for print com-

prehension. Only subtle differences in the relative strength of speech-print convergence in several regions of interest were found between the languages. Particularly, speech-print convergence was slightly higher for transparent Spanish than opaque English and Hebrew in left parietal-temporal areas including supramarginal gyrus (SMG) and supplementary motor area (SMA), both associated with phonological processing (Herman et al., 2013). Conversely, in that study of skilled adults speech-print convergence was higher for English and Hebrew relative to Spanish in several regions including left angular, fusiform (FG) and inferior temporal gyri (ITG) implicated in lexical-semantic processing in speech (Hickok and Poeppel 2007) and in print (Pugh et al., 2010). Cross-language differences in speech-print convergence may be particularly pronounced at the initial stages of reading acquisition, where adequate grapheme to phoneme transparency binding may be more beneficial for learners of transparent script. In this context the comparison of the young readers of the alphabetic scripts that differ primarily in terms of the orthographic transparency, but other visuo-spatial characteristics of the writing system are controlled for, is the most informative. Rueckl's et al. (2015) study looked only at mature adults which cannot give insight into the relative similarities or differences in emergent learning and in early trajectories.

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To acquire reading in the alphabetic script, a child needs to master the ability to rapidly and accurately map letters to existing phonological representations (Bradley and Bryant 1983; Wagner and Torgesen 1987). Thus the development of efficient cross modal mapping skills, which depends upon early phonological skills, has been shown to reflect the integrity of left hemisphere regions such as superior temporal sulcus (STS, van Atteveldt et al., 2004). Literacy acquisition reorganizes the brain, strengthening the functional and anatomical link between phonemic and graphemic representation which results in changes to perisylvian language areas toward modality independent processing (Dehaene et al., 2015). The emergence of speech-print convergence reflects this brain plasticity presumably by allowing print stimuli to leverage biologically specialized networks for many aspects of language processing (Chyl et al., 2018; Preston et al., 2016). While beginning readers of transparent Polish showed speech-print convergence in bilateral IFG and STG/MTG, it was absent in pre-readers matched for demographics (Chyl et al., 2018) and thus appeared to be a key biomarker of this plasticity (Dehaene et al., 2015). Furthermore, in readers a positive correlation between convergence and reading skill was found in the left STG/MTG suggesting that greater convergence was associated with better reading skills. That relation was also seen in English beginning readers where reading readiness (as indexed by phonological awareness) was correlated with greater spatial speech-print convergence in the left STG/MTG (Frost et al., 2009). Importantly, the extent of the print-speech convergence predicted reading performance achieved one (Marks et al., 2019) or two years later (Preston et al., 2016) in English beginning readers.

Orthographic transparency, a parameter indicating how regular letter-phoneme correspondences are in the given script is a well-known factor influencing reading acquisition. Children learning to read in opaque orthographies are slower in acquiring this skill than children learning to read in transparent orthographies (Ziegler and Goswami 2005; Hanley et al., 2004; Seymour et al., 2003) and thus might show lower spatially defined speech-print convergence i.e. less ability of reading to leverage the machinery of language specialization. The orthographic depth hypothesis (Katz and Frost 1992) as well as the psycholinguistic grain size theory (Ziegler and Goswami 2005) suggest that learning to read based on phonological decoding is more advantageous for transparent orthographies, while lexically driven processes are relatively more beneficial in opaque scripts, already from the fairly early in literacy training. English and Polish constitute good examples of orthographies that are relatively contrastive in terms of their orthographic transparency. English is generally considered to be one of the more opaque alphabetic orthographies (e.g. Share, 2008; Frost, 2012) as a given grapheme can often be pronounced differently in different contexts (the lack of consistency partly dependent on the grain size of the computed phonological representation so that at the grapheme to phoneme level consistency is lower than at the onset/rime grain). For instance, the /ea/ vowel (as in head, heat, steak) has many different pronunciations. Polish, in contrast is relatively transparent where the grapheme to phoneme correspondence is relatively high for reading (Schuppert et al., 2017). As we hypothesize that print-speech integration reflects the binding of graphemes to phonemes especially in early reading stages, this integration must be in some sense easier to learn in orthographies with a one-to-one/few (i.e. Polish) mapping, as opposed to one-to-many (i.e. English). As the development of print speech convergence must begin with this cross modal mapping this suggests speech-print convergence may have a very different impact or time course in contrastive orthographies. It is therefore possible that convergence will be delayed in English relative to Polish. With respect to the neural representations of these two languages related to orthographic transparency, it is reasonable to expect differences in the engagement of brain regions taxed during reading along dorsal and ventral pathways. The former was implicated in reading in more shallow orthographies, while the latter in more opaque orthographies both by monolingual (Paulesu et al., 2000) and bilingual readers (Meschyan and

Hernandez, 2006; see also Lallier and Carreiras, 2018, for review).

Using three complementary analytic approaches we examined print and speech processing networks and their convergence in 100 young users of two contrasting languages: opaque English and fairly transparent Polish (Schuppert et al., 2017), performing an identical fMRI language localizer task. We expected that the general pattern of activity for print and speech will be similar across two languages, with speech-print convergence present in IFG and STG/MTG. Orthographic transparency effects should occur in dorsal regions related to phonological decoding with higher speech-print coupling in Polish than English, while the reversed pattern is expected in ventral regions involved in visual word recognition.

## 2. Methods

### 2.1. Participants

Inclusion criteria for the Polish sample were as follow: at least typical IQ as indicated by the norms of the Raven's Progressive Matrices (> 25 centile; Jaworowska and Szustrowa 2011) and Wechsler Intelligence Scale for Children (>70 IQ scale; Matczak et al. 1997), birth at term (>37 weeks), right-handedness, monolingualism, no history of neurological or language impairments and good quality of the fMRI scan (< 20% of motion-affected volumes identified with ART toolbox, see below for details). All English-speaking children who met the Polish inclusion criteria with IQ assessed with Wechsler Preschool and Primary Scale of Intelligence (>70 IQ scale; WPPSI-IV, 2014) or Wechsler Abbreviated Scale of Intelligence (>70 IQ scale; WASI-II, 2012) were included in the analysis (50 out of 82 collected datasets). Polish-speaking children were a part of the larger cohort ( $N = 120$ ), and were matched pairwise with their American peers for age, word reading efficiency (N of words read correctly per minute) and a time gap between scan and behavioural test using the Hungarian optimization algorithm (Kuhn 1955, Chyl et al., 2018) to reduce group differences. As a result, data from 50 Polish children (M age = 7.11, SD = 0.99, min = 5.41, max = 9.21) and 50 American children (M age = 6.95, SD = 0.98, min = 4.75, max = 8.93) were selected for the current analysis. This sample size resulted in power higher than 80% for the fMRI analyses (Desmond and Glover 2002). Similarly, this sample size gave us 80% power for detecting medium and large effects (Cohen's  $d \geq 0.50$ ) in between-group comparisons, as revealed with G\*Power (Faul et al., 2009, 2007). All procedures were approved by the ethics committees in Poland (University of Warsaw Ethic Committee) and United States (Yale University School of Medicine). All parents gave written informed consent to the study and children agreed orally in compliance with human subjects protection and Helsinki Declaration guidelines.

### 2.2. Behavioral measures

Word reading and pseudoword reading were tested with the Decoding Test (Polish; Szczerbiński and Pelc-Pękała, 2013) and Test of Word Reading Efficiency (English; Torgesen, Wagner, and Rashotte 2012), and the raw score was scaled to the words per minute (WPM) measure. Since tests were not perfectly balanced for length, i.e. English words in the tests were shorter than Polish items, we estimated also letter per second measure. Rapid automatized naming (RAN) was tested with the object naming subtest of the Rapid Naming Test (Polish; Fecenec et al., 2013) and the Comprehensive Test of Phonological Processing (English; Wagner et al., 2013). Here, raw scores were scaled to the items per second score. In this subscale, all items in both languages were one-syllable words. On both sites the subscale of color naming was also applied, but since the Polish color names were longer than English (2.6 syllables on average versus 1.25), we did not include this measure in the analyses. Phonological awareness (PA) was examined with the phoneme deletion test in Polish (Szczerbiński and Pelc-Pękała 2013) and English

(Wagner et al., 2013) and transformed into the normalized z-scores for each group. These PA tests had different instructions, items and timing so no direct comparison between languages was performed. Additionally, maternal and paternal education represented by the highest obtained grade (scaled to the 1-7 scale in both groups) was compared between the groups.

### 2.3. fMRI and task procedure

Before the scanning session, children at both sites were familiarized with the task and scanner environment in a mock-scanner. An identical fMRI paradigm was used at both sites for print and speech activation localization (Malins et al., 2016). The event-related task consisted of four stimulus conditions: (1) printed real words, (2) spoken real words, (3) printed symbol strings, and (4) noise-vocoded spoken words to minimize phonetic content. Conditions (3) and (4) can be considered as low-level nonlinguistic control conditions that are matched in physical characteristics to the printed linguistic stimuli (length and visual complexity on screen) and to the spoken linguistic stimuli (dynamic frequency and amplitude content). However, linguistic content has been eliminated (orthographic and phonetic, respectively). Conditions (1) and (2) are referred to as word activity (print activity or speech activity), and when contrasted with control conditions (1 > 3) and (2 > 4) are considered word specific activity (print specific or speech specific). This design activates the language network, and is sensitive to individual differences in reading skills in both adults (Malins et al., 2016) and children (Chyl et al., 2018, Chyl et al., 2019).

Polish children were asked to pay attention to the stimuli, but no explicit task was given to the participants. American children were also asked to pay attention to the stimuli and after each run two simple recognition questions about the auditorily presented words were asked (e.g. „Did you hear the word „grass“?“, „did you hear the word „snow“?). This step was introduced in order to make sure that children were focused on the task. However, listening is automatic and reading should occur implicitly even without explicit instruction to read (Price, Wise, and Frackowiak 1996).

On each trial, four different stimuli from the same condition were presented in rapid succession in a ‘tetrad’, designed to evoke strong activation within a relatively short imaging time. Each visual stimulus was presented for 250 ms, followed by a 200 ms blank screen, whereas each auditory stimulus was allowed 800 ms to play out. ‘Jittered’ intertrial intervals were employed with occasional ‘null’ trials resulting in ITIs ranging from 4 to 13 s (6.25 s on average). The task was performed in two runs, each lasting 5:02 min. All conditions were presented in each run, with 48 trials per run presented pseudorandomly, with restriction not to repeat one condition more than three times in a row. This resulted in 24 total trials per condition, and 96 total stimuli per condition. Stimuli were presented using Presentation software (Neurobehavioral Systems, Albany, CA) in Poland and E-Prime software in the United States.

### 2.4. fMRI data acquisition

fMRI data at each site were acquired on Siemens 3T Magnetom Trio scanners using similar whole-brain echoplanar imaging sequences, 12-channel head coil (32 slices, slice-thickness 4 mm, TR = 2000 ms, TE = 30 ms, FOV = 220 × 220 mm<sup>2</sup>, matrix size = 64 × 64, voxel size = 3 × 3 × 4). There was a difference in the flip angle parameter (Polish = 80°, American = 90°). Anatomical data was acquired using a T1 weighted MP-RAGE sequence (176 slices, slice-thickness = 1 mm, TR = 2530 ms, TE = 3.32 ms, flip angle=7°, matrix size=256\*256, voxel size= 1 × 1 × 1 mm). Generalized Autocalibrating Partial Parallel Acquisition (GRAPPA) acceleration was used at the Polish site (iPAT = 2), but not at the American site. To correct scanner differences, we performed iterative smoothness equalization and included signal-to-fluctuation-noise-ratio (SFNR) as a covariate in all between group comparisons (Friedman, Glover, and Fbirm

Consortium 2006). SFNR maps were calculated for the preprocessed (realigned, normalized and smoothed) fMRI time series with fBIRNQA tools ([https://www.nitrc.org/projects/bxh\\_xcede\\_tools/](https://www.nitrc.org/projects/bxh_xcede_tools/)) as the average BOLD signal across time divided by the corresponding temporal standard-deviation image, which was then averaged over runs. Whole brain SFNR was not statistically different between the groups (mean PL = 138.36, mean US = 150.755; t(98) = 1.784, p = 0.076).

### 2.5. fMRI data processing

The preprocessing and analyses were performed using SPM12 (Wellcome Trust Center for Neuroimaging, London, UK) and AFNI version 17.3.09 (Cox 1996). In SPM12, images were realigned to the first functional volume. Then structural images from single subjects were coregistered to their mean functional images. Coregistered anatomical images were segmented using pediatric tissue probability maps (generated with Template-O-Matic toolbox). Next, DARTEL was used to create a group-specific template and flow fields based on segmented tissues (Ashburner 2007). Functional images were normalized to MNI space with 2 × 2 × 2 mm voxel size using compositions of flow fields and a group-specific template. Next, in the univariate analyses, Gaussian spatial smoothing was performed using the 3dBlurtoFWHM option in AFNI, which allows for the „adaptive smoothing” method, and the data were smoothed to equalize estimated FWHM at 10 mm, which is considered to be a standard in the used method, corresponding to conventionally used 6–8 mm gaussian convolution kernel (Eklund et al., 2016). This method, enabling the gradual increase of estimated spatial correlation, allowed to equalize smoothing estimates in the two samples, which was important as in PL children smoothing was initially increased due to the GRAPPA reconstruction method. The data were modeled using the canonical hemodynamic response function convolved with the experimental conditions and fixation periods. Movement regressors were added to the design matrix using ART toolbox to reject motion-affected volumes surpassing the movement threshold of 3 mm and a rotation threshold of 0.05 radians. On average 4.02 volumes were removed in the US, and 6.74 in PL samples, with non-significant difference between the groups.

### 2.6. fMRI data analysis

To examine speech-print convergence we applied three different analytic approaches: co-activation maps for print and speech on the whole brain and in selected regions of interest (ROIs), correlation analysis between brain activation to print and speech in selected ROIs and representational similarity analysis (RSA). Co-activation analysis tested the overlap between activation to print and speech, by the means of the whole brain conjunction (Rueckl et al., 2015; Marks et al., 2019), but also for individual subjects by counting the number of co-active voxels in the a priori ROIs (Marks et al., 2019). Correlational analysis focused primarily on the individual differences, providing fine-grained information about the similarities in the strength of activation for print and speech in the two languages (Rueckl et al., 2015; Marks et al., 2019). Representational similarity analysis is a multivariate approach that measures combinatorial effects across voxels (i.e. spatial activation patterns) and is regarded as a complement to the univariate approaches (Davis and Poldrack, 2013). The RSA approach has been widely adopted in previous studies, including speech (Evans et al., 2015) and reading (Zhao et al., 2017). The present study for the first time applied searchlight RSA examining print-speech convergence from a multivariate perspective. Searchlight RSA is sensitive to spatial activation patterns that cannot be estimated by univariate activation and can provide fine-grained information about similarities between neural representations and conceptual models. In the present study, searchlight RSA was applied to confirm the univariate results and to reveal subtle regions that represent both print and speech information but fail to show significant activation.



Selection of ROIs was guided by the results on skilled adults (Rueckl et al., 2015) as well as meta-analyses of reading studies (Linkersdörfer et al., 2012; Richlan 2012). Eight ROIs were included in the analyses: left and right STG/MTG, left and right IFG - with additional division to pars opercularis and pars triangularis in the left hemisphere (L IFG\_oper and L IFG\_tri, respectively), left SMG, left ITG and left FG. The ROIs were created using Anatomical Automatic Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) masked with the functional activation defined as a sum of all activated regions for all contrasts of interest from both groups. Left angular gyrus and right SMG also reported by Rueckl and colleagues (Rueckl et al., 2015) were outside the activation mask and thus were not included as ROIs. In the ROI analyses we applied conservative Bonferroni correction for multiple comparisons to avoid false positives (i.e.  $p < 0.05/8 = p \leq 0.00625$ ). ROIs are additionally described by Talairach atlas and available for visualization and download (see Data/code availability statement). In each ROI analysis, the local SFNR, estimated by averaging SFNR across voxels in each ROI (one number per ROI; for the SFNR values in each ROI see data available at OSF), was added as the regressor to the regression model and standardized residual values were used in the analysis.

**Co-activation.** Independent samples *t*-tests identified voxels that were significantly active at  $p < 0.005$ , FDR cluster corrected, for print and speech, print>symbols and speech>vocalized speech, separately for the two groups. Group conjunctions were explored based on conjunction null logic (Friston, Penny, and Glaser 2005) in which we identified voxels that were significantly active at  $p < 0.005$ , FDR-corrected, for both PL and US in 4 conditions: print, speech, print>symbols (print specific) and speech>vocalized speech (speech specific).

To examine language differences within each anatomical ROI, we created a metric of speech-print convergence based on co-activation, defined as the total number of voxels for each participant that were significantly activated ( $p < 0.05$ ) both for speech and print (conjoint probability  $p < 0.0025$ ; (Frost et al., 2009; Preston et al., 2016; Marks et al., 2019). In addition, the number of voxels activated at  $p < 0.05$  across the functional mask defined as a sum of all activated regions for all contrast of interest from both groups for 1) spoken or 2) printed stimuli were computed to control for the relative degree of brain activation for each participant and together with 3) local SFNR were used as regressors of no interest.

**Correlation.** To further examine print-speech convergence within the ROIs, we performed the correlation analysis. In this analysis, regression parameter estimates (averaged within the ROIs) for print and speech were used to compute *r*-Pearson correlation coefficients across subjects in each group. Within each ROI, the print parameter estimates were correlated with speech parameter estimates separately for the two groups. Then, the correlation coefficients for each ROI were compared between languages using the Fisher *r*-to-*z* transformation, suitable for the comparison of *r* correlation coefficients.

**Representational similarity analysis (RSA).** The searchlight RSA was conducted for each subject by using RSA toolbox (Kriegeskorte, Mur, and Bandettini 2008; Nili et al., 2014), and was constrained in gray matter with a gray matter mask generated from AAL template (Tzourio-Mazoyer et al., 2002). After obtaining trial-wise estimates with beta-series regression (Rissman, Gazzaley, and D'Esposito 2004), 96 trial-wise beta images were used to assess representational dissimilarity between every pair of trials within a spherical searchlight kernel with 9 mm radius centered at each gray matter voxel, resulting in a representational dissimilarity matrix (RDM) map in which each voxel contains a 96 by 96 RDM. Specifically, the representational dissimilarity between a pair of trials was estimated by one minus Pearson correlation ( $1 - r$ ) where the correlation was calculated between beta values within a searchlight kernel. The speech-print convergence model was constructed as a RDM where the printed and spoken words are regarded as identical so that the trial pairs of real words hold highest similarity (valued 0 in RDM) while other trial pairs yield lowest similarity (valued 1 in RDM). The representational similarity between neural representation and the

speech-print convergence model were estimated by calculating Spearman's rho between the RDM maps and the model RDM for each voxel. The resulting Spearman's rho maps were then Fisher-*z* transformed and submitted to second-level statistical tests. All RSA results are presented on the voxel threshold  $p < 0.005$ , FDR cluster corrected.

Moreover, activation to print only or speech only, as well as print>symbols and speech>vocalized speech was compared between the languages within the 8 ROIs, corrected for SFNR. Whole-brain group comparisons of print>symbols and speech>vocalized speech, as they are potentially more susceptible to cross-scanner differences (Rueckl et al., 2015) are not included to the main body of the manuscript, but added as the supplement (see Supplementary Material 3).

Finally, following the analyses reported in previous papers (Chyl et al., 2018, Marks et al., 2019), we explored the relation between speech-print convergence and reading proficiency. The correlation between the number of co-active voxels for print-speech and print specific - speech specific conditions in the 8 ROIs (corrected for print activity, speech activity and local SFNR) and number of words read per minute for the two groups is reported in the Supplementary Material 4.

Figures were prepared with Nipype (Gorgolewski et al., 2011).

### 3. Data/code availability statement

Behavioral data, ROI data, masked ROIs, parameters of the items used in fMRI experiment as well as the experimental protocols used at both sites are available online (<https://osf.io/982ks>). Moreover, the ROIs can be downloaded and visualized as the Neurovault Collection (<https://neurovault.org/collections/8487/>).

## 4. Results

### 4.1. Behavioral results

Demographics and test performance is presented in Table 1. Since the groups were matched for reading, no differences were found for word reading score. However, independent samples *t*-test showed significant differences between Polish and American children in the estimated scores of letters in pseudowords read per second, with Polish children reading more efficiently than American. No difference was found in the pseudowords per minute, and this result reflects the differences in test items, as pseudowords used in the US group were shorter than in the Polish sample. US children were faster in the RAN objects subscale. There was no difference between the fathers' education, but mothers of the PL group obtained higher level of education. Since the Polish and American tests measuring PA differed in many parameters (instructions, items, difficulty level), we decided not to compare the PA score between the groups.

### 4.2. fMRI results

#### 4.2.1. Language-independent activation

Fig. 1 and Table 2 reports the results of the group conjunction analysis revealing language-independent networks for printed and spoken word recognition. For print, the regions that were commonly employed by Polish and American children were bilateral occipital, frontal and temporal cortex. Print specific (print > symbols) activation common for both groups was present solely in the left IFG and precentral gyrus (PrCG). For speech and speech specific (speech > vocalized) conditions both groups activated bilateral temporal and frontal cortex, but speech specific activation was less extensive.

#### 4.2.2. Speech-print convergence

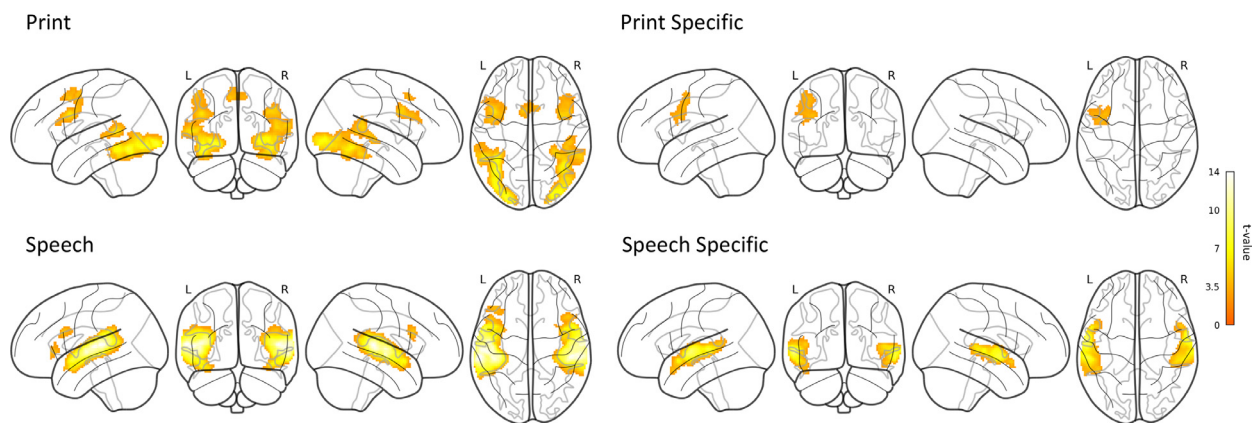
Fig. 2 presents regions active for print and speech (for details see Table S1), as well as regions convergently active for print and speech in both groups (Table 3). Whole brain convergence analysis for speech and print revealed activation in bilateral IFG and MTG/STG for both

**Table 1**

Demographics and test performance in Polish (PL) and American (US) children: Means, (Standard Deviations) and [95% CIs].

	PL (n=50)	US (n=50)	test	p-value	Cohen's d
<b>Demographic measures</b>					
Age in years	7.11 (0.98) [6.84; 7.38]	6.95 (0.99) [6.68; 7.22]	$t(98) = 0.816$	ns	0.16
Sex: M = males, F = females	18 M, 32 F	22 M, 28 F	$\text{Chi}^2(1, N = 100) = 0.667$	ns	
Mother Education	6.46 (0.96) [6.19; 6.73]	5.78 (1.09) [5.48; 6.08]	$t(98) = 3.332$	$p = 0.001$	0.66
Father Education	6.00 (1.41) [5.61; 6.39]	6.02 (1.17) [5.70; 6.34]	$t(98) = 0.076$	ns	0.02
<b>Behavioral measures</b>					
Word reading:	41.96(30.81)	50.58 (33.81)	$t(98) = 1.332$	ns	0.27
words read correctly per minute	[33.42; 50.50]	[41.21; 59.95]			
Pseudoword reading:	27.02 (16.70)	23.38 (20.01)	$t(98) = 0.987$	ns	0.20
pseudowords read correctly per minute	[22.39; 31.65]	[17.83; 28.93]			
Letters in words read per second (estimated)	3.28 (2.90)	3.33 (2.78)	$t(98) = 0.086$	ns	0.02
	[2.48; 4.08]	[2.56; 4.10]			
Letters in pseudowords read per second (estimated)	2.35 (1.78)	1.31 (1.41)	$t(98) = 3.266$	$p = 0.002$	0.65
	[1.86; 2.84]	[0.92; 1.70]			
RAN:	0.86 (0.20)	0.95 (0.23)	$t(98) = 2.474$	$p = 0.015$	0.42
objects named per second	[0.80; 0.92]	[0.89; 1.01]			

ns - not significant

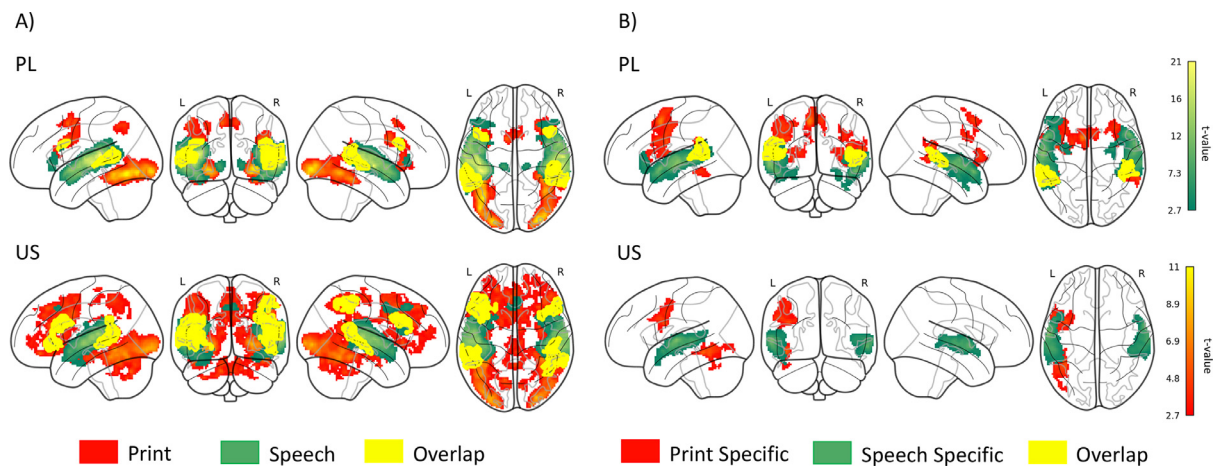


**Fig. 1.** Group conjunctions showing brain regions that are active for both groups in Print, Print Specific (print > symbols), Speech, Speech Specific (speech > vocoded) (threshold for each contrast  $p < 0.005$ , FDR cluster corrected) for each language.

**Table 2**

Brain regions that are active in both groups for Print, Speech, Print Specific (Print > Symbols) and Speech Specific (Speech > Vocoded). Hemisphere (H), coordinates (x, y, z), t statistic for the peak (t) and number of voxels (v) is reported.

Brain region	H	x	y	z	t	v
<b>Print Conjunction</b>						
Inferior Occipital, Middle Occipital, Fusiform, Inferior Temporal, Cerebellum (crus1), Cerebellum (6), Middle Temporal, Lingual	L	-40	-60	-14	8.27	2184
Middle Temporal, Inferior Occipital, Superior Temporal, Fusiform, Inferior Temporal, Middle Occipital, Calcarine, Lingual, Cerebellum (6), Lingual	R	38	-86	-2	7.40	3112
Middle Temporal, Superior Temporal	L	-54	-44	8	6.38	693
Precentral, Inferior Frontal (tri, oper)	L	-42	10	30	5.80	942
Inferior Frontal (oper, tri), Precentral, Middle Frontal	R	40	4	32	5.08	642
Supplementary Motor Area (L&R)	L&R	-8	10	48	4.67	288
<b>Print Specific Conjunction</b>						
Precentral, Inferior Frontal (oper, tri)	L	-36	6	26	4.12	561
<b>Speech Conjunction</b>						
Superior Temporal, Middle Temporal, Rolandic Operculum, Superior Temporal Pole, Insula, SupraMarginal, Heschl, Postcentral	L	-60	-28	10	14.28	5439
Superior Temporal, Middle Temporal, Rolandic Operculum, Insula, Heschl, Superior Temporal Pole, SupraMarginal, Postcentral	R	50	-28	8	14.03	4921
Inferior Frontal (tri, oper)	L	-46	18	24	4.67	221
Inferior Frontal (tri, oper)	R	46	20	24	4.65	235
Inferior Frontal (tri, orb), Insula	L	-40	30	2	4.11	195
<b>Speech Specific Conjunction</b>						
Middle Temporal, Superior Temporal, Superior Temporal Pole, Rolandic Operculum, Heschl, Insula, Middle Temporal Pole	L	-60	-8	0	10.04	2017
Superior Temporal, Middle Temporal, Superior Temporal Pole, Heschl, Rolandic Operculum, Insula	R	62	-4	-6	8.54	1473



**Fig. 2.** A) Intersect maps showing brain regions that are active for Print only (red), Speech only (green), or both Print and Speech (yellow) B) Intersect maps showing brain regions that are active for Print Specific (Print > Symbols; red), Speech Specific (Speech > Vocoded; green), or both Print Specific and Speech Specific (yellow). Threshold for each modality  $p < 0.005$ , FDR cluster corrected

**Table 3**

Print-Speech Convergence in Polish and American groups. Threshold for each contrast  $p < 0.005$ , FDR-corrected. Hemisphere (*H*), coordinates (*x*, *y*, *z*), *t* statistic for the peak (*t*) and number of voxels (*v*) are reported.

Brain region	<i>H</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>	<i>v</i>
PL Print - Speech Convergence						
Middle Temporal, Superior Temporal	L	-48	-44	10	5.96	668
Superior Temporal, Middle Temporal	R	60	-42	12	5.17	945
Inferior Frontal (tri, oper)	L	-44	14	26	4.40	213
Inferior Frontal (tri, oper)	R	46	16	28	4.16	217
PL Print - Speech Specific Convergence						
Middle Temporal, Superior Temporal, SupraMarginal	L	-48	-42	10	5.27	872
Superior Temporal, Middle Temporal	R	42	-42	6	3.61	288
US Print - Speech Convergence						
Middle Temporal, Superior Temporal	L	-54	-46	10	5.70	892
Inferior Frontal (tri, oper, orb), Insula, Putamen	L	-46	18	24	5.46	1097
Superior Temporal, Middle Temporal	R	50	-40	14	5.18	789
Superior Temporal Pole	L	-34	0	-18	4.62	190
Inferior Frontal (tri, oper), Precentral, Middle Frontal	R	52	22	26	4.36	503
Inferior Parietal, Angular	R	52	-42	56	3.80	265

Polish and English with an additional cluster of overlap in the right parietal cortex for American children. Speech specific and print specific intersection was visible only in Polish children in bilateral MTG/STG at the given threshold.

Co-activation analysis within the 8 ROIs revealed that there were more voxels co-active for both print and speech for Polish than English in the right STG/MTG (M PL (residuals) = 0.29, SD = 1.01; M US (residuals) = -0.29, SD = 0.87;  $t(98) = 3.065$ ,  $p = 0.003$ ), while the reversed pattern was present in the left FG (M PL (residuals) = -0.28, SD = 0.55; M US (residuals) = 0.28, SD = 1.22;  $t(98) = 2.979$ ,  $p = 0.004$ ). No significant differences between the groups were found for speech specific - print specific co-activation, i.e. the groups did not differ in the number of co-active voxels.

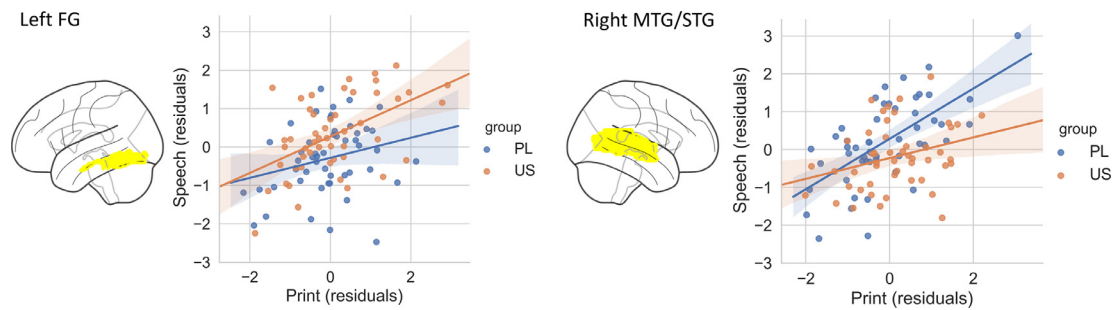
Similar results were observed in the brain activation correlation analysis within the ROIs (Fig. 3, Table S2). While the correlation between regression parameter estimates for print processing and speech processing in the left FG was significant in American children ( $r = 0.518$  [0.282; 0.696],  $p < 0.001$ ) it did not reach significance in Polish children ( $r = 0.259$  [0; 0.501],  $p = 0.07$ ), however the difference between correlation coefficients was not significant ( $z = 1.5$ ;  $p = 0.13$ ). In case of the right STG/MTG, the correlation was significant in both languages ( $r = 0.636$  [0.438; 0.778],  $p < 0.001$  and  $r = 0.301$  [0.030; 0.537],  $p = 0.034$  for PL and US respectively), but was significantly higher in Polish than English ( $z = 2.14$ ;  $p = 0.03$ ). Additionally, the significant difference in the correlation coefficients was found in the left IFG (pars

opercularis;  $z = 2.2$ ,  $p = 0.028$ ), with significant correlation found in PL ( $r = 0.626$  [0.422; 0.770],  $p < 0.001$ ) and at a trend level in US ( $r = 0.274$  [0.00; 0.515],  $p = 0.054$ ). Again, no significant differences between the groups (surviving correction for multiple comparisons) were revealed for correlations between regression parameter estimates for print and speech specific contrasts.

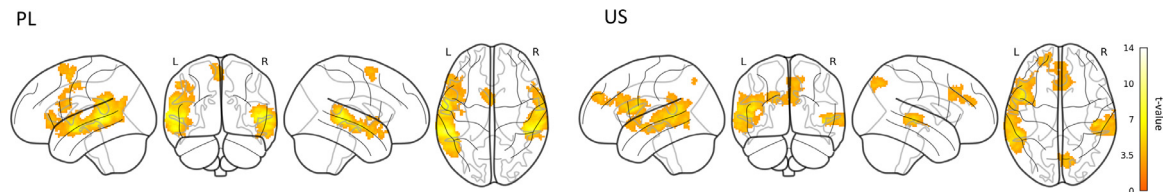
A high degree of similarity in speech-print convergence between Polish and American children was also revealed in RSA analysis (Fig. 4 and Table 4). Again, the convergence as measured by similarity between brain response to speech and print was present in bilateral temporal regions and left frontal areas. Additionally, some descriptive differences between PL and US groups could be observed such as the additional involvement of the right STG in the PL group and the additional involvement of left frontal area in the US group. However, no significant differences between the groups were found in RSA ROI analyses.

#### 4.2.3. Language-specific activation

Next, we examined group differences in activation to print only or speech only, as well as print>symbols and speech>vocoded speech within the 8 ROIs. For visual conditions, only one significant difference was found, with English involving left IFG pars triangularis more than Polish in response to print ( $t(98) = 3.163$ ,  $p < 0.002$ ). In print specific condition no differences were found. For speech, English had higher activation than Polish in the left FG ( $t(98) = 3.167$ ,  $p = 0.002$ ) and ITG ( $t(98) = 4.243$ ,  $p < 0.001$ ), while left MTG/STG was more involved in



**Fig. 3.** Scatter plots of the correlation between print and speech activation in representative areas showing greater correlation in the left fusiform gyrus (FG) for opaque English (Left) and in the right STG/MTG for more transparent Polish (Right). Local SFNR value was regressed from the raw values. Fisher’s R-to-Z transform was performed to check the difference between the languages.



**Fig. 4.** RSA convergence maps in Polish and American children (threshold  $p < 0.005$ , FDR cluster corrected).

**Table 4**

RSA Convergence maps in Polish and American groups. Threshold for each contrast  $p < 0.005$ , FDR-corrected. Hemisphere (*H*), coordinates (*x*, *y*, *z*), t-statistic for the peak (*t*) and number of voxels (*v*) are reported.

Brain region	<i>H</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>	<i>v</i>
<b>PL RSA Convergence</b>						
Middle Temporal, Superior Temporal, SupraMarginal, Inferior Frontal (tri, orb), Superior Temporal Pole, Rolandic Operculum, Angular, Insula	L	-58	-38	2	9.63	5533
Superior Temporal, Middle Temporal, Superior Temporal Pole, Middle Temporal Pole	R	52	-36	2	8.58	2406
Inferior Frontal (oper, tri), Precentral, Postcentral	L	-44	8	20	4.50	653
Supplementary Motor Area	L&R	-2	6	56	4.45	368
<b>US RSA Convergence</b>						
Middle Temporal, Superior Temporal, Inferior Frontal (tri, oper), Rolandic Operculum, Precentral, SupraMarginal, Postcentral, Superior Temporal Pole, Insula, Middle Frontal, Inferior Temporal	L	-48	10	14	6.48	4652
Middle Temporal, Superior Temporal	R	46	-28	-2	5.96	875
Middle Cingulum (L&R), Superior Frontal (L&R), Medial Superior Frontal (L&R), Anterior Cingulum (L&R)	L&R	-16	52	28	4.53	1005
Precuneus (L&R), Cuneus (L&R)	L&R	8	-72	46	4.45	354

Polish than English ( $t(98) = 3.280$ ,  $p = 0.001$ ). Polish produced also a higher response in the left MTG/STG than English in speech specific condition ( $t(98) = 3.314$ ,  $p = 0.001$ ).

### 5. Discussion

Here, we present how young beginning readers of Polish and English process spoken and printed words. We particularly focused on the aspect of conjoint processing of print and speech (convergence), a hallmark of the successful literacy acquisition in previous works across both languages (Chyl et al., 2018; Preston et al., 2016) and common for different languages in skilled adult readers (Rueckl et al., 2015). This is the first study to examine print-speech convergence in matched samples of emergent readers in contrastive orthographies which provides insight into the relative similarities and differences in the early trajectories of this hallmark. We also tested language-related similarities and differences in processing print and speech separately.

With regard to convergence our results show a striking resemblance to previous findings (Rueckl et al., 2015), and demonstrate that incorporating print into the existing speech network is similar in contrasting languages, not only in adulthood but also at the beginning of reading acquisition. Bilateral IFG and MTG/STG were activated by print and speech in both Polish and American children. Complementary RSA analysis, sensitive to spatial activation patterns, confirmed language invari-

ant similarities between neural representations of both speech and print in the left IFG and bilateral MTG/STG. Speech-print convergence in the previous study (Rueckl et al., 2015) was additionally present in the left parietal cortex, which may be related to the task demands. Here, we measured implicit activation to speech and print with no task given to the participants, while in a previous study participants made semantic judgments. Nevertheless, we provide evidence that the core speech-print convergence is independent of reading experience and the fMRI task (also observed for word matching in younger children, Marks et al., 2019), at least for typical reading development.

When we tested in individual subjects the size of speech-print convergence in several ROIs of the language network, we found that Polish children had more co-active voxels in the right STG/MTG than American, while a reversed pattern was present in the left FG. These results were supported by the additional correlational analysis showing stronger speech-print correlations of neuronal activity in the right STG/MTG in Polish than English. In the left FG, the speech-print correlation was significant only in English, but not in Polish (though the difference between languages did not reach significance). The results of these two univariate methods to assess print-speech convergence in individual subjects (used interchangeably in previous studies) are well aligned, and generally show that increased spatial co-activity between print and speech goes in line with increased linear relation between the magnitude of response to speech and print. Since STG/MTG is generally associated



with phonological processing (STG: Yi, Leonard & Chang, 2019; MTG & STG: Mathur, Shultz & Wang, 2020) and left FG with lexical processing (Cohen et al., 2002), our results support the predictions from both orthographic depth hypothesis (Katz and Frost, 1992) (and the psycholinguistic grain size theory (Ziegler and Goswami 2005)). As reading in transparent orthographies is thought to rely more on phonological processes, whereas reading in opaque orthographies is assumed to rely more on lexico-semantic processes, it has been hypothesized that orthographic depth might modulate the engagement of brain regions along the dorsal (sub lexical) and ventral (lexical) pathways (Carreiras, Armstrong & Dunabeitia, 2018). First evidence for such a pattern was demonstrated by Paulesu et al., (2000) where readers of shallow orthography (Italian) activated dorsal reading pathway compared to their peers, while readers of opaque orthography (English) showed more activation in the ventral pathway. Here, we observe that Polish children rely more on the right STG/MTG associated with phonological decoding for reading, while American children reading in English rely more on left FG which is associated with lexical processing. These findings are also in line with Rueckl et al., (2015) who found stronger print-speech coupling in the regions related to phonological processing - left SMG and SMA (Stoekel et al., 2009) in orthographically transparent Spanish than in English and Hebrew. Orthographically opaque English and Hebrew had stronger convergence not only in left FG, but also in the left angular gyrus, ventral left MTG and ITG, as well as the anterior IFG (pars triangularis), all thought to be related to the lexical semantic processing (Hagoort, 2019). In contrast to current findings, the right STG and SMG also showed stronger correlations for the comparison of opaque versus transparent orthographies. However, both right and left STG were identified as neural structures underlying phonemic representations in multivariate analyses (Arsenault and Buchsbaum, 2015), and undamaged right STG/STS in patients with Wernicke's aphasia retains their ability to discriminate between phonemes (Binder, 2003). Besides the potential influence of reading experience and employed task, some of the examined by Rueckl et al., (2015) adult participants were multilingual (in contrast to currently examined monolingual children), which might have affected the pattern of brain activation. Nevertheless, the reported differences in speech-print convergence between beginning and skilled readers of contrasting orthographies are rather subtle, supporting the claim that the reading network is deeply constrained by the organization of the brain network also at the beginning of reading acquisition. This conclusion is also supported by the additional analysis showing no differences between the groups in the relation between reading skill and speech-print or speech specific - print specific coactive voxels (see Supplementary Material 4). This analysis showed that among all ROIs, a significant positive correlation between reading and coactive voxels was found solely in the left MTG/STG (both groups) and left IFG pars triangularis (PL only) for speech specific - print specific convergence. This result is in line with the previous findings suggesting that convergence in these regions is related to reading skills (Chyl et al., 2018; Preston et al., 2016). We thus conclude, that not only the neural representations for speech-print convergence is similar between contrasting orthographies but also its relation to reading development in beginning readers seems alike.

Print stimuli in both languages evoked activity in bilateral inferior occipital, temporal and frontal areas, thus the classical network for reading (Dehaene et al., 2010; Martin et al., 2015; Pugh et al., 2001, 2010). At the same time, print specificity (print>symbols) was found only in left IFG and PrCG in both groups. Engagement of the left IFG/PrCG in early reading was shown in both typical and struggling readers across different languages (Pollack, Luk, and Christodoulou 2015) and was associated with phonological recoding (Pugh et al., 2010) or top-down cognitive control (Pollack, Luk, and Christodoulou 2015). We previously showed that the left IFG/PrCG shows stronger activation to words in readers compared to age-matched pre-readers (Chyl et al., 2018) and its significance for reading increases with time and reading instruction (Chyl et al., 2018). Currently we demonstrate that PrCG/IFG activity

is the only common word specific activation in young readers of two languages. Study on young German readers found that print>symbols contrast induced activity in IFG and MTG (Bach et al., 2013), and a similar pattern was found in Polish. Nonetheless, the American group activated merely the left hemisphere. We speculate that this result may be related to the similar orthographic transparency of Polish and German (Schuppert et al., 2017). However, in print>symbols comparison no significant differences between the groups were found. Only for print itself stronger involvement of the left IFG (pars triangularis) was found for English than Polish. This structure is often implicated in semantic processes of reading and stronger activation in the English speaking cohort may reflect a stronger reliance on lexical-semantic processes.

Common speech activation was found in the bilateral temporal and frontal regions, while speech specific activation was limited to the bilateral temporal cortex. Similarly, (Rueckl et al., 2015) examining adults showed that STG was active for speech regardless of language. It is not surprising, considering the biological constraints imposed by perisylvian specialization for speech. However, reading training was shown to reorganize these areas and enhance speech processing in planum temporale/STG (Monzalvo and Dehaene-Lambertz 2013), and speech specific activity in the left STG was shown to correlate with reading efficiency in beginning readers (Chyl et al., 2018). Here, we found that Polish children engaged left STG/MTG stronger than American for both speech and speech specific contrasts. This result might suggest that the reorganization of the speech network is a consequence of reading acquisition proceeding faster and more easily in readers of a transparent script. An alternative explanation relates to the fMRI task material, as Polish words matched for frequency and length to American words had higher number of syllables and phonemes (Syllables: mean PL = 1.28, mean US = 1;  $t(382) = 6.912, p < 0.001$ ; Phonemes: mean PL = 3.85, mean US = 3.54;  $t(382) = 3.220, p = 0.002$ ) and it has been shown before that STG is particularly sensitive to these linguistic properties (Perrachione et al., 2017). Higher activation for American than Polish was found in the left FG and ITG, but only for speech. Activity of the ITG in response to speech was observed in 9-year olds but not pre-reading 6-year olds in the previous study (Monzalvo and Dehaene-Lambertz 2013) and was explained as the sign of the orthographic influences on speech perception.

Current findings come from a multicenter study, and certain differences in both behavioral tests and fMRI data acquisition have to be acknowledged. For instance, attentional processes might have been enhanced in the American group, since they were asked control questions after each experimental run. We have tried to diminish potential sources of unwanted variance by carefully matching the subjects for demographics and reading skills and following FBIRN recommendations for handling multicenter fMRI data (Glover et al., 2012). However, it is possible that not all of the confounding factors have been cancelled out. Moreover, short written word presentation times (250 ms) should be considered as the limiting factor in our study. Some of the youngest readers might not have been able to successfully engage in the reading processes at all in such a short time, which could have resulted in decreased ability to detect the reading-related activity at the group level. Especially in the context of implicit processing task, the observed findings might be a mixture of the specific effects related to reading and nonspecific effects related to attention or engagement with the task (Chyl et al., 2018).

In summary, we have demonstrated that in the two groups of children speaking different languages the neural pattern of print and speech processing is remarkably similar. Importantly, the speech-print convergence is present in both groups, yet again suggesting that incorporating orthographic processing into the speech pathways shaped by evolution shows a great deal of universality for different languages and scripts at least for this skill related mechanisms. Following the results of the previous study with adult participants (Rueckl et al., 2016) we provide evidence that this effect is present at the early stage of the reading acquisition. However, orthographic transparency of the language may also evoke somewhat different strategies in early reading, as suggested by the orthographic depth hypothesis (Katz and Frost 1992). In our study

American children showed stronger involvement of the fusiform gyrus for print-speech coupling, associated with lexical processing, while the Polish children showed higher speech-print convergence in the right middle and superior temporal gyri, associated with phonological processing.

### Declarations of Competing Interest

None.

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### Supplementary materials

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