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Reading and spelling skills are differentially related to phonological processing: Behavioral and fMRI study

Agnieszka Dębska[a,*], Katarzyna Chyl[a], Gabriela Dzięgiel[a], Agnieszka Kacprzak[a,b], Magdalena Łuniewska[a], Joanna Plewko[a], Artur Marchewka[c], Anna Grabowska[d], Katarzyna Jednoróg[a]

[a] Laboratory of Language Neurobiology, Nencki Institute of Experimental Biology, Polish Academy of Sciences, Warsaw, Poland
[b] Faculty of Psychology, Warsaw University, Poland
[c] Laboratory of Brain Imaging, Nencki Institute of Experimental Biology, Polish Academy of Sciences, Warsaw, Poland
[d] Faculty of Psychology, SWPS University of Social Sciences and Humanities, Warsaw, Poland

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ABSTRACT

The manuscript reports a study on a large sample (N = 170) of Polish speaking 8–13 year old children, whose brain activation was measured in relation to tasks that require auditory phonological processing. We aimed to relate brain activation to individual differences in reading and spelling. We found that individual proficiency in both reading and spelling significantly correlated with activation of the left ventral occipito-temporal cortex encompassing the Visual Word Form Area which has been implicated in automatic orthographic activations. Reading but not spelling was found to correlate with activation in the left anterior dorsal stream (anterior supramarginal and postcentral gyri). Our results indicate that the level of both reading and spelling is related to activity in areas involved in the storage of fine-grained orthographic representations. However, only the reading level is uniquely related to activity of regions responsible for the articulation, motor planning and grapheme-to-phoneme correspondence, which form the basis for effective decoding skill.

1. Introduction

Phonological awareness (PA) is the ability to represent the sound structure of words and to identify and manipulate syllables, onsets, rimes and phonemes. It is widely accepted that some aspects of phonological awareness are prerequisites for successful literacy acquisition: PA enables children to make sense of the grapheme-phoneme correspondences they are learning and to deploy that knowledge effectively for reading and spelling of orthographically unfamiliar words (Pritchard et al., 2012; Seidenberg and McClelland, 1989). The level of PA is the most important predictor of reading and spelling development (de Jong and van der Leij, 2003; Ehri et al., 2001; Torgesen et al., 1994; Ziegler and Goswami, 2005). Early deficits in PA are considered a major cause of reading as well as spelling difficulties (*the phonological deficit hypothesis*, Ramus et al., 2003; Snowling, 1998).

Even though problems with phonological processing influence both reading and spelling (Caravolas et al., 2001; Friend and Olson, 2008; Jobard et al., 2003), the relationship between phonology and each of these two skills might be different. Phonologically, spelling is more difficult than reading even for typical readers, as there are usually more ways to spell a phoneme than to read a grapheme (Holmes and Carruthers, 1998; Kessler and Treiman, 2001). In transparent orthographies with high grapheme-to-phoneme regularity (such as Finnish, German, Greek or Polish, see e.g. Scheppert et al., 2017) isolated poor reading is associated with the difficulties in retrieval of phonological representations from long-term memory (demonstrated by lower rapid naming scores) and isolated spelling deficit with lower performance in phonological awareness tasks (German: Wimmer and Mayringer, 2002, Finnish: Torppa et al., 2017). In opaque orthography like English, there is also evidence that distinct cognitive processes underly reading and spelling based on reports of typical readers with an unexpected poor spelling level (Holmes and Quinn, 2009; Holmes and Castles, 2001; Frith, 1980). Frith (1985) argued that unexpected poor spellers are characterized by inadequately refined orthographic representations. In line with this theory, the *lexical quality hypothesis* claims that differences in precision of lexical representations explain why typical reading might coexist with poor spelling skills: poor orthographic representation suffices for reading but not for spelling (Andrews and Hersch,

* Corresponding author at: Laboratory of Language Neurobiology, Nencki Institute of Experimental Biology, Pasteur 3, 02-093 Warsaw, Poland.
E-mail address: a.debska@nencki.gov.pl (A. Dębska).

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2010). Taking into account that high-quality orthographic representations are also developed based on phonological representations (Wimmer and Mayringer, 2002) we might expect that poor spelling would be characterized by the inefficient phonological skills.

Cognitive representations of the orthographic and phonological features of words are closely intertwined in reading development. To read a known word aloud, children need to combine their knowledge of pronunciation with an orthographic pattern or, for unknown words, make a letter-to-sound translation (Coltheart, 2005). It is well established that efficiency with which phonological and orthographic information is combined is associated with successful reading (Barron, 1994; Seidenberg and McClelland, 1989; Zecker, 1991). When phonological representations are integrated with orthographic structures of letters and words, they form a basis for a high quality lexicon which supports reading and spelling. In both skilled and novice readers, but not dyslexic individuals, orthographic information is spontaneously activated during auditory phonological processing or spoken word recognition in a phenomenon called the *auditory orthographic activation effect* (Ziegler and Ferrand, 1998, for a review see: Barron, 1994). One example of auditory activation of orthographic information is that it is more difficult for skilled readers to judge whether two spoken words rhyme when they are spelled differently (Seidenberg and Tanenhaus, 1979). It remains unknown whether spelling proficiency is associated with automatic orthographic activations in the same way as reading skill. There is only limited evidence suggesting that there are no differences in the auditory orthographic effect in comparing poor spellers (but typical readers) and typical readers and spellers (Martin, 1984).

So far, the neuroimaging research has focused only on orthographic representations shared by reading and spelling (Purcell et al., 2011, 2017). Rapp and Lipka (2011) directly investigated the neural basis of orthographic representations in English and found shared substrates for both domains of reading and spelling in the left mid-fusiform regions and in the posterior inferior frontal gyrus. The left ventral occipitotemporal cortex (lvOT, encompassing the Visual Word Form Area -VWFA, recognized as a storage of orthographic representations, Dehaene et al., 2002) was involved in orthographic processes to an equal extent in both reading and spelling tasks. Similar results, confirming the crucial role of the left-mid-fusiform gyrus for orthographic representations in both domains came from studies by Purcell et al. (2011, 2017) and Tsapkini and Rapp (2010).

In contrast to the issue of orthographic representations, it is still unclear though what the neural basis of spelling and reading is and the extent to which they share cognitive phonological representations. No studies have tried to directly distinguish their involvement in the same group of participants. The phonological brain network responsible for effective phonological processing encompasses mostly left hemisphere areas like the inferior parietal lobule (including supramarginal and angular gyri), inferior frontal cortex, postcentral and precentral gyri, superior and middle temporal gyri, and fusiform and dorsolateral prefrontal cortex (e.g. Bitan et al., 2007; Booth et al., 2006; Cao et al., 2008; Hoeft et al., 2006; Poldrack et al., 1999; Kovelman et al., 2011). The activity of the phonological brain network is closely related to reading. For example, the activity of the left superior temporal and ventral occipitotemporal brain regions observed during exposure to phonological tasks was positively correlated with reading level (Brennan et al., 2013; Bolger et al., 2008). Additionally, children with dyslexia (Desroches et al., 2010; Kovelman et al., 2011) or with familial history of reading impairments when performing auditory phonological tasks show atypical neural activations, even before the reading onset (Dębska et al., 2016; Raschle et al., 2012). Neuroimaging studies support the hypothesis that it is not only the activity of the phonological brain network that is responsible for efficient reading but that the strength of phonological-orthographic co-activations also play a strong role. In a study by Desroches et al. (2010) examining spoken language processing of children which are typical readers (but not children with difficulties) showed activation of the lvOT area. According to the authors, the automatic influence of orthographic information during auditory phonological tasks is indicative of strong decoding skills which support reading proficiency.

To our knowledge there are no similar studies linking phonological brain network activation with spelling level. While atypical neural patterns observed during phonological operations have been explicitly associated with poor reading abilities, studies were performed on groups in which spelling and reading deficits often co-occur (Andreou and Baseki, 2012; Landerl et al., 1997).

To bridge this gap, we analyse the behavioral performance, as well as neuronal activity, of 170 school-aged (8–13 years) Polish-speaking children during auditory phonological tasks that required different levels of phonological awareness. The choice of the tasks matched the development of phonological awareness (in Polish, Raźniak, 2016, as well as in English, Carroll et al., 2003).

Based on previous studies of isolated reading and spelling deficits in other transparent orthographies (Moll et al., 2009; Torppa et al., 2011; Manolitsis and Georgiou, 2015; Wimmer and Mayringer, 2002), we expected to find a unique association between reading and rapid naming as well as between spelling and phonological awareness. At the neuronal level, we expected an association between both spelling and reading level and brain activity in the language areas located in the left hemisphere such as the temporo-parietal and lvOT, where hypoactivations during phonological processing were previously found in readers with both reading and spelling difficulties.

2. Methods

2.1. Participants

All participants were part of a larger group (N = 197) involved in a study on the cognitive heterogeneity of dyslexia, approved by the University of Social Sciences and Humanities Ethical Committee and in accordance with the Declaration of Helsinki. Written consent was acquired on behalf of the children from their parents. All participants were Polish-speaking monolinguals. They were right-handed and born at term. None of them had any history of neurological illnesses or brain damage and none had symptoms of ADHD or low IQ (below 85). Data from 27 children were excluded from the analysis due to excessive motion during fMRI scanning, technical problems during fMRI acquisition, failure to complete fMRI scanning, or not following instructions. The resulting analysis included a total of 170 children (63 girls and 107 boys) aged 8.25–12.95 years (10.32 years on average).

2.2. Behavioral measures

Participants completed a wide set of tests measuring reading and spelling capacities, rapid naming, and phonological awareness. All tests belong to the normalized battery for dyslexia diagnosis in two versions: one for 3rd and beginning 4th graders and one for the late 4th and 5th graders (Bogdanowicz et al., 2009). In the phoneme deletion task, participants had to delete a phoneme given by an experimenter (e.g. say "banana" without "b"). Rapid automatized naming was tested with subtests of object and colour as well as letter and digit naming (Fecenec et al., 2013). Three reading tests from the normalized battery were used to cover all important aspects of reading in a transparent orthography: word reading test, pseudoword reading test, and reading with lexical decision. The word reading test measures accuracy of reading while the other two tests measure speed and fluency. The word reading test for younger children consisted of 50 words to read and, for older children, 85 words. Words differed in the level of complexity and frequency of occurrence in Polish between the two versions. The two other reading tests had identical set of items in two versions. In pseudoword reading, the task was to accurately read a list of pseudowords in 60 s (max. 70 items). In the reading with lexical decision test, the task was to cross out pseudowords from the set of 78 items (50 real words and 28 pseudowords) in 60 s. The pseudowords used in these tests were pronounceable but had had no close word neighbors. Only one normalized spelling test for the examined age range was available in the battery (spelling to dictation). This test also had two versions, one for younger children (a story consisting of 85 words) and another for older children (a story consisting of 171 words). The individual results in all tasks for every child were transformed into normalized (sten) scores based on the psychometric scale from the battery. To obtain the reading skill factor (READ) we averaged the normalized (sten) scores from the three reading tests and transformed this average into Z-scores. The spelling skill factor (SPELL) was created by transforming the standardized (sten) scores from the spelling test (written spelling to dictation) into Z-scores.

2.3. fMRI tasks

Tasks performed in the scanner were created to examine different aspects of phonological processing. We list them below ordered from the easiest to most advanced: pseudoword comparison (pseudoword matching), rhyming (last triphone comparison), and single phoneme level of processing (first phoneme matching, see: Kaminska, 2003). Firstly, children performed trial tasks in a mock-scanner to get familiar with the experimental procedure. During the scanning session, children completed three phonological tasks with pseudowords stimuli. In all tasks, the stimuli were presented aurally via headphones. At the beginning of each task, an image of two cartoon dragons was presented for five seconds. Next, each dragon provided one pseudoword with a 500 ms break between dragons. The yes/no decision was made by pressing a corresponding button. The inter-trial interval varied from 4.5 to 7.5 s (6 s on average). Each task lasted on average 180 s and was presented in a separate fMRI run. In a pseudoword matching task, participants had to judge if two pseudowords were the same or different (e.g. *tol* - *tol*). In a rhyming task, they needed to assess if two pseudowords rhymed or not (e.g. *bowane* - *gapane*). In a first phoneme matching task, participants had to decide whether two pseudowords started with the same phoneme or not (e.g. *plok* - *psat*). All tasks consisted of 30 trials. Stimuli were presented using Presentation software (Neurobehavioral Systems, Albany, CA).

2.4. fMRI data acquisition and analyses

fMRI data were acquired on a 3 T Siemens Trio scanner using whole-brain echo planar imaging sequence with 12-channel head coil (32 slices, slice-thickness 4 mm, TR = 2000 ms, TE = 30 ms, flip angle = 80°, FOV = 220 mm2, matrix size: 64 × 64, voxel size 3 × 3 x 4 mm). Anatomical data were acquired using T1 weighted 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).

The neuroimaging data pre-processing and analyses were performed using Statistical Parametric Mapping (SPM12, Welcome Trust Center for Neuroimaging, London, UK) run on MATLAB R2016b (The MathWorks Inc. Natick, MA, USA). In the first step, all images were realigned to the participant mean. Next, T1-weighted images were segmented using paediatric tissue probability maps (Template-O-Matic toolbox was used with the matched pairs option). The functional images were normalized to MNI space via flow fields acquired from T1-weighted image co-registered to mean functional image. Finally, the normalized images were smoothed with an 8 mm isotropic Gaussian kernel. The data was modelled for each run using the canonical hemodynamic response function convolved with the tasks. Besides adding movement regressors to the design matrix, the ART toolbox was used to reject motion-affected volumes by modelling them in the design matrix. Subjects were included if a minimum 80% of volumes from each run were artefact-free. Artifactual volumes were identified using a movement threshold of 3 mm and a rotation threshold of 0.05 radians (based on Raschle et al., 2012).

The general linear approach was used to analyse the experimental tasks. On the first level of analysis, experimental trials were contrasted with implicitly modelled rest periods (baseline). The zero-order correlation and partial correlation analysis were performed in a multiple regression model with age of participants as a covariate.

To look at independent influence of one skill but not the other in the brain regions correlated with READ and/or SPELL factors, we performed partial correlation analysis masked at the group analysis level by significant results obtained in the zero-order correlations.

The results are reported at $p < 0.005$ height threshold corrected for multiple comparisons at $p < 0.05$ using cluster extent (see e.g.: Wang et al., 2018). Cluster significance was determined by using AFNI's 3dClustSim based on 10,000 iterations and spatial autocorrelation function (ACF) of mixed Gaussian and mono-exponential form. Parameters for the ACF were the average of all 170 individual subject's values obtained using AFNI's 3dFWHMx (Cox et al., 2017). The cluster sizes reached 517 voxels for the zero-order correlation analyses and 60 voxels for the partial correlation analyses. The anatomical structures were identified with the use of xjView toolbox.

3. Results

3.1. Behavioral performance

The sample included children ranging from poor to excellent readers and spellers. Descriptive statistics for all 170 children including mean scores, ranges, and standard deviations are presented in Table 1. READ and SPELL factors were found to be highly correlated ($r = 0.72$, $p < 0.001$). The statistics of group performance in the phonological tasks are presented in Table 2. Both SPELL and READ factors showed significant positive correlations with all of the phonology related tasks. However, as revealed by the partial correlation analysis, the relations for each of the factors were different. Only the READ variable controlled for SPELL correlated positively with both RAN tasks ($r = 0.30$, $p < 0.001$ for (objects & colours) and $r = 0.44$, $p < 0.001$ for (digits & letters). Both factors were found to be significantly related to the phonologically demanding, phoneme deletion task (SPELL: $r = 0.19$, $p < 0.05$, READ: $r = 0.23$, $p < 0.005$, see Table 2).

3.2. In-scanner performance

Overall performance in all tasks was high. On average 72% in the first phoneme matching task, 76% in the rhyming task, and 82% in the pseudoword matching task. Again, both the READ and SPELL variables correlated positively with performance in the three phonological tasks (READ: $r = 0.22$ for the pseudoword matching task, $r = 0.29$ for the rhyming task, $r = 0.28$ for the first phoneme matching task, all $p < .001$; SPELL: $r = 0.31$ for the pseudoword matching task, $r = 0.41$ for the rhyming task, $r = 0.36$ for the first phoneme matching task, all $p < .001$). In partial correlations, only SPELL controlled for READ significantly correlated with all tasks (for details see Table 3).

Table 1
Descriptive statistics for reading, spelling, and phonological tests.

test	Mean	SD	Range
Sight-word reading [1]	4.7	2.2	1–10
Pseudoword reading[1]	4.3	1.8	1–10
Reading with a lexical decision[1]	4.6	2.3	1–10
Writing to dictation[1]	3.7	2.1	1–10
RAN [1](color andobjects)	4.1	2.1	1–10
RAN[1] (digits and letters)	4.4	2	1–9
Phoneme deletion[1]	4.7	2	1–10

[1] Standard test scores (stens) adjusted for age of participants. [2]Raw scores.

Table 2
Level of production and phonological abilities: correlations and partial correlations.

Variable	Correlations with READ	Correlations with SPELL	Correlations with READ after controlling for SPELL	Correlations with SPELL after controlling for READ
RAN (color&objects)	0.51**	0.44**	0.30**	0.12
RAN (digits&letters)	0.55**	0.36**	0.44**	−0.06
Phoneme deletion	0.48**	0.47**	0.23**	0.19*

* $p < 0.05$.
** $p < 0.005$.

3.3. fMRI Results

First, whole-brain regression analysis (zero-order correlation) was performed for READ and SPELL factors and each phonology related task (see Table 4 and Fig. 1). In the pseudoword matching task, the READ factor was positively correlated with the activity of an extensive cluster including the left inferior parietal lobule (IPL), supramarginal (SMG) and postcentral gyri (PostCG), and with activity in left inferior and middle occipital cortex including the lvOT. In the rhyming task, positive correlations with READ were present in the left IPL. In the first phoneme matching task, the READ factor again correlated positively with activations in the left IPL whereas the SPELL factor correlated positively with activations in the lvOT. There were no overlapping positive correlations with both READ and SPELL skills in the same task. However, the posterior lvOT cluster was associated with both skills in two different tasks (the pseudowords matching for READ and the first phoneme matching for SPELL).

Second, partial correlations in the multiple regression model were performed to identify structures associated with one skill when controlled for the other. These partial correlations can indicate when a significant relation between a given variable and activation exists that was not explained simply be the correlation of two factors. Partial correlation analysis performed for the data from the pseudowords matching task showed significant positive correlation between READ and activation in the left IPL, SMG, PostCG, and lvOT. In the same task, a significant interaction effect was found for two clusters. The left SMG and PostCG correlated significantly only with READ ($r = 0.32$ for SMG and $r = 0.28$ for PostCG, $p < 0.01$) but not with SPELL (see Fig. 2). In the rhyming task, positive partial correlations were found for the READ factor in the left SMG. Finally, in the first phoneme matching task, positive partial correlations were found in the left IPL and PostCG for the READ factor. Additionally, a unique positive correlation was found in the lvOT for the SPELL factor. Detailed results are presented in Table 5.

4. Discussion

The goal of our study was to examine shared and distinct phonological representations associated with reading and spelling skills using an individual differences approach in a large sample of school-aged children.

Our data shows that the level of spelling and reading was highly correlated ($r = 0.72$, $p < 0.001$). This is in line with previous research showing that shared variance ranges from 40% (Tierney and Shanahan, 1991) up to 85% (Berninger et al., 2002), depending on the factors

Table 4
Significant correlations of individual spelling and reading skills with brain activations in phonological tasks.

Brain region	H	x	y	z	T	Voxels
Task 1. Pseudoword matching						
READ						
PostCentral, Inferior Parietal & Supramarginal*	L	−60	−24	30	4.55	2346
Inferior & Middle temporal, Middle & Inferior Occipital, Fusiform*	L	−42	−50	−10	4.88	597
SPELL						
—						
Task 2. Rhyming						
READ						
Supramarginal, PostCentral, Inferior parietal	L	−54	−34	32	4.30	676
SPELL						
—						
Task 3. First Phoneme Matching						
READ						
Supramarginal, Postcentral, Inferior parietal*	L	−48	−30	46	4.06	855
SPELL						
Inferior & Middle temporal, Fusiform	L	−40	−46	−14	4.02	694

Height threshold at $p < 0.005$, cluster corrected at $p < 0.05$.
* Remains significant at $p < 0.001$.

chosen for the analysis. Partial correlations with the range of phonological tasks showed that reading was uniquely correlated with performance in rapid naming tasks (in both subtests: letters and digits as well as colours and objects). Both reading and spelling showed an association withthe more phonologically demanding phoneme deletion task. Spelling skill correlated with performance in all in-scanner phonological tasks that required phonological awareness on the level of both syllable and phonemes (pseudoword matching, first phoneme matching, and rhyming), when controlling for the level of reading. Results were in agreement with our hypotheses on specific association between rapid naming and reading on one hand and phonological awareness and spelling on the other. The unique link between performance in the rapid naming task and reading is in line with results from previous behavioral studies on transparent orthographies (Moll et al., 2014; Torppa et al., 2011; Wimmer and Mayringer, 2002). In such orthographies, the association between grapheme and phoneme is highly regular and the main challenge for young readers is to read fluently and rapidly (in more opaque orthographies like English, reading difficulties are reflected mostly in lower reading accuracy). Less regular phoneme-to-grapheme correspondence in spelling requires proper knowledge of

Table 3
Accuracy in fMRI phonological tasks: correlations and partial correlations.

Variable	Mean accuracy %	Correlations with READ	Correlations with SPELL	Correlations with READ after controlling for SPELL	Correlations with SPELL after controlling for READ
Pseudoword matching	82%	0.22**	0.31**	−0.01	0.23**
Rhyming	76%	0.29**	0.41**	−0.01	0.31**
First Phoneme Matching	72%	0.28**	0.36**	0.02	0.24**

** $p < 0.005$.

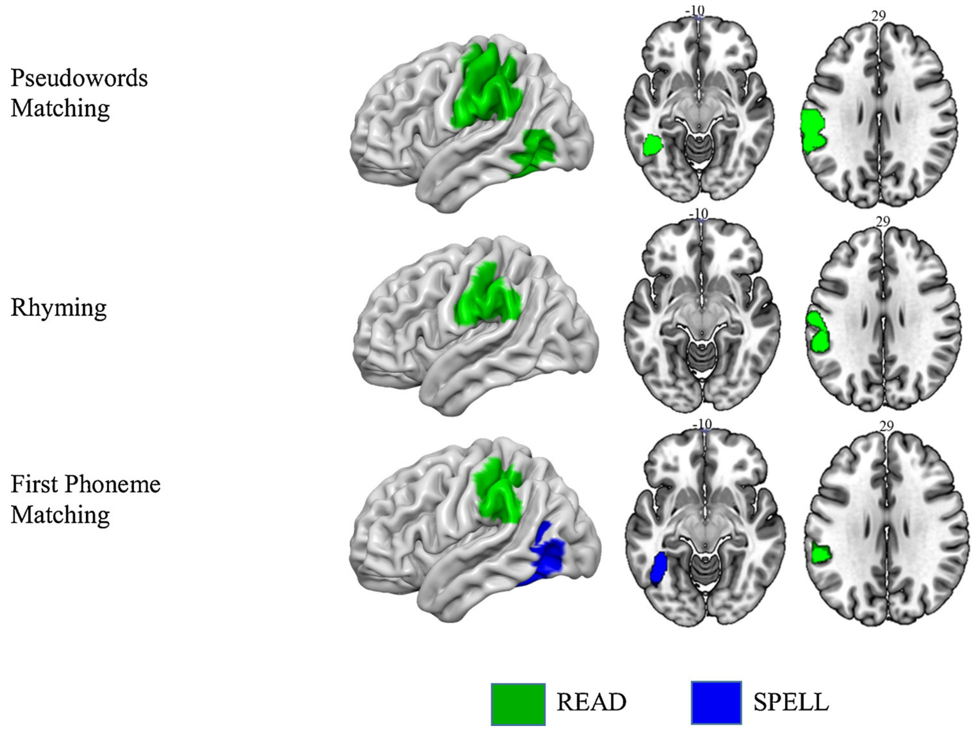

Fig. 1. Clusters showing significant positive correlations with READ and SPELL skills in three phonological tasks.

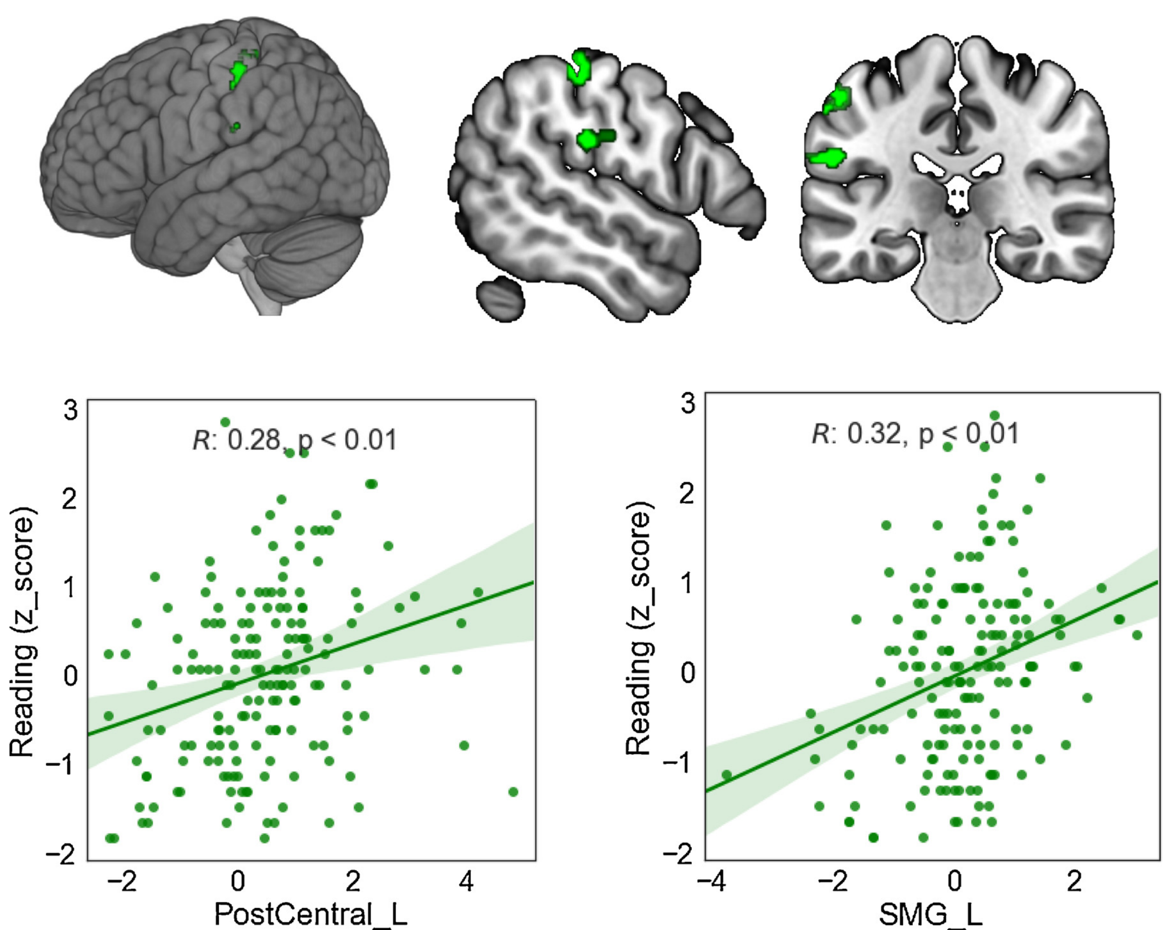

Fig. 2. Structures engaged in the interaction effect (positive correlations with reading but not spelling) in the pseudoword matching task.

Table 5
Significant partial correlations of individual spelling and reading skills with brain activations in phonological tasks.

Brain region	x	y	z	T	Voxels
Task 1. Pseudoword matching					
READ					
Postcentral, Inferior parietal, Supramarginal (L)*	−58	−20	26	3.99	1308
Fusiform, Inferior temporal (L)*	−42	−50	−12	3.71	325
INTERACTION READ X SPELL					
Postcentral (L)	−54	−30	54	2.94	100
SupraMarginal (L)	−54	−26	24	3.28	63
SPELL					
—					
Task 2. Rhyming					
READ					
SupraMarginal (L)*	−60	−40	30	3.62	75
SPELL					
—					
Task 3. First Phoneme Matching					
READ					
Inferior Parietal, Postcentral (L)	−52	−36	48	3.21	120
SPELL					
Fusiform (L)	−38	−48	−8	3.06	71

Height threshold at $p < 0.005$, cluster corrected at $p < 0.05$.
* Remains significant at $p < 0.001$.

specific orthographic representations which are developed by accurate association with phonological representations (Wimmer and Mayringer, 2002). This might explain the unique correlation of spelling and phonological awareness in Polish.

At the neuronal level, we expected positive correlation between both spelling and reading skills and brain activity in the left temporo-parietal and lvOT regions. Partial correlations allowed us to distinguish which factor is uniquely associated with the activation of a given brain structure when controlling for the shared variance of both skills. Consistently, positive partial correlation was found for reading skill in the left temporo-parietal region across all phonological tasks. Also, the left SMG and PostC regions showed a significant interaction effect in the pseudoword matching task. Activity in these regions correlated positively with the reading but not spelling level (see: Figs. 2 and 3A). The left SMG is considered as storage for phonological representations (Raizada and Poldrack, 2007; Zevin and McCandliss, 2005; Burton et al., 2000a, b; Koelsch et al., 2009; Paulesu et al., 1993). Its role in phonological processing was also confirmed in a TMS study (Sliwinska, 2015) which compared activity in phonological and semantic tasks. The authors concluded that the specific role of the left SMG in processing phonology is based on the covert articulation and monitoring of inner speech. This articulatory loop is associated with the crucial role of the left SMG in phoneme-to-grapheme conversion (Booth et al., 2006; Horwitz et al., 1998; Hoeft et al., 2006; Kronbichler et al., 2007; Pugh et al., 2000; Das et al., 2011; Shaywitz et al., 1998; Shaywitz et al., 2002; Shaywitz and Shaywitz, 2005). Since the left SMG is essential for sub-lexical processing of phonemes it takes part in pseudoword or non-word processing (Vigneau et al., 2006; Xu et al., 2001). Alterations of this region were described in children and adults with dyslexia and attributed to problems with integration of letters and speech sounds (Pugh et al., 2001; Blau et al., 2009; Booth et al., 2006). Overall, according to the "anterior dorsal stream hypothesis" (Schwartz et al., 2012), phonological errors are associated with the pre- and post-central gyri and supramarginal gyrus rather than with the superior temporal structures, indicating the fundamental role of motor planning and programming in phonological processing (Foundas et al., 1998; Cloutman et al., 2009; Tremblay et al., 2003).

Both spelling and reading skills correlated with activation of the lvOT encompassing the Visual Word Form Area (cVWFA: described as "classical" VWFA in Lerma-Usabiaga et al., 2018; Dehaene et al., 2002; Gaillard et al., 2006), even though all tasks were aurally presented and based on pseudowords. In our study, clusters showing correlations for reading and spelling in pseudoword matching and first phoneme matching tasks are located close to each other and to the cVWFA or middle occipito-temporal sulcus (see: Fig. 3B, euclidian distance equal to 7.6 mm and 6 mm for lvOT cluster correlated with READ and SPELL, respectively). The cVWFA, as opposed to the posterior VWFA (pVWFA, posterior occipito-temporal), is connected with the temporo-parietal cortex and the inferior frontal gyrus and is responsible for integration of information from language and language-like stimuli (Lerma-Usabiaga et al., 2018). Recent studies indicate that orthographic representations in the lvOT are activated in a top-down manner during speech processing (Dehaene and Cohen, 2011; Ludersdorfer et al., 2016; Ludersdorfer et al., 2015), even when they are not required explicitly by the task (Wang et al., 2018; Castles et al., 2011). Desroches et al. (2010) showed that activity of the lvOT during an auditory rhyming task was positively correlated with non-word reading. This was interpreted as indicating that this region serves as an important gateway to orthographic, sub-lexical information. It has also been recognized as a shared source of orthographic representations for reading and spelling (Purcell et al., 2011, 2017, Rapp and Lipka, 2011; Tsapkini and Rapp, 2010). Our individual differences analysis showed positive correlation with this region in the pseudoword matching task with reading and in

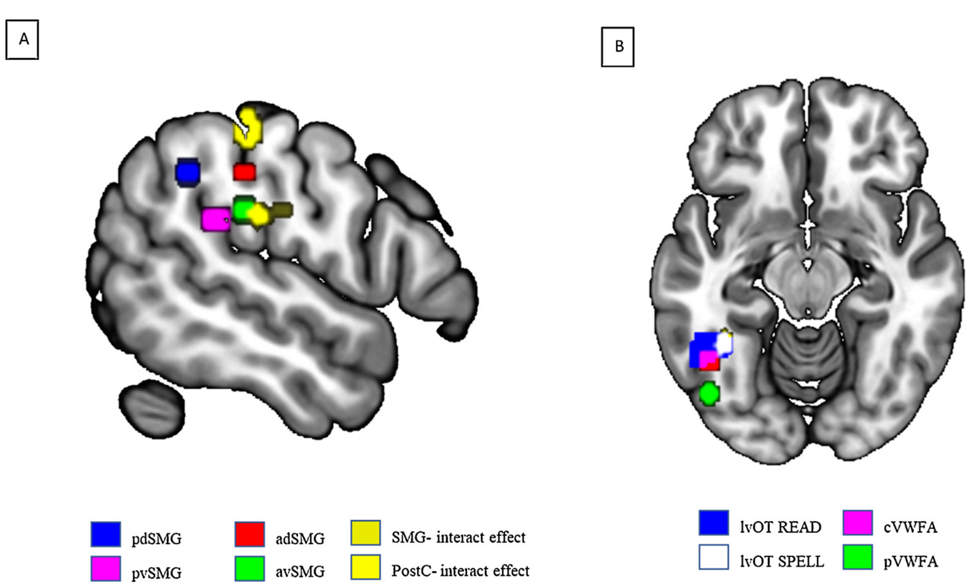

Fig. 3. ROI comparisons. (A) Comparison of functionally distinct phonological regions in the left SMG (Oberhuber et al., 2016), pd = posterior, a = anterior, d = dorsal, v = ventral, and regions correlated only with the reading but not the spelling factor (SMG, PostC). (B) Comparison of lvOT regions (Lerma-Usabiaga et al., 2018), pVWFA = posterior VWFA, cVWFA = classical VWFA, overlapped with the areas correlated with the spelling and reading factors.

the first phoneme matching task with spelling, supporting the idea that the lvOT region is shared by both reading and spelling skills. This is, to our knowledge, the first evidence that orthographic co-activations elicited by phonological processing are related not only to efficiency in reading but also efficiency in spelling. Spelling skill was uniquely correlated with lvOT activation in the first phoneme matching task. This is the most orthographically demanding task that required processing on the level of single phonemes (onset) and therefore involved automatic orthographic decoding. In line with Desroches et al (2010), increased activation of the lvOT in skilled readers during phonological processing might be a mark of orthographic co-activations for whole word-units. The significance of the lvOT role in language processing seems to depend on the orthographic demands of the task.

More research on automatic orthographic effects and spelling is needed. In this study, the SPELL factor was based on one standardized test which might have limited measurement reliability compared to the READ factor which was based on three. Also, our results are limited to the group of beginning to intermediate readers with at least two years of reading experience of a transparent language. Developmentally and across orthographies, the relationship between RAN, PA, reading, and spelling seems to be more complex. For example, left SMG might show positive association with spelling level at the beginning of literacy acquisition since grapheme-to-phoneme conversion is crucial for early development of both reading and spelling. Recent longitudinal, cross-language study (Georgiou et al., 2012) demonstrated unidirectional relations between reading and spelling (early reading predicted spelling) across different orthographies with early decoding ability being a prerequisite for both skills. On the other hand, Landerl et al. (2019) revealed that performance in RAN has consistent influence on reading level across orthographies whereas PA as a predictor was more dependent on the stage of education and orthographic complexity.

5. Conclusions

Our investigation revealed that in transparent orthography (Polish), children's individual reading ability was predominantly related to performance in rapid naming. Their spelling ability was related to operations on phonemes and syllables. On the neural level, efficient reading and spelling was associated with the activity of the left ventral occipitotemporal region encompassing the Visual Word Form Area which has been implicated in automatic orthographic co-activations. Unique partial correlation for reading but not spelling was found in the left anterior dorsal stream (anterior supramarginal and postcentral gyri). Overall, our results indicate that both level of reading and spelling is related to activity in areas involved in the storage of fine-grained orthographic representations. However only reading is uniquely related to activity of regions associated with articulation, motor planning, and grapheme-to-phoneme correspondence.

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