

Distinct patterns of brain function in children with isolated spelling impairment: New insights

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ABSTRACT

Studies investigating reading and spelling difficulties heavily focused on the neural correlates of reading impairments, whereas spelling impairments have been largely neglected so far. Hence, the aim of the present study was to investigate brain structure and function of children with isolated spelling difficulties. Therefore, 31 children, aged ten to 15 years, were investigated by means of functional MRI and DTI. This study revealed that children with isolated spelling impairment exhibit a stronger right hemispheric activation compared to children with reading and spelling difficulties and controls, when engaged in an orthographic decision task, presumably reflecting a highly efficient serial grapheme-phoneme decoding compensation strategy. In addition, children with spelling impairment activated bilateral inferior and middle frontal gyri during processing correctly spelled words and misspelled words, whereas the other two groups showed bilateral activation only in the misspelled condition, suggesting that additional right frontal engagement could be related to generally higher task demand and effort. DTI analyses revealed stronger frontal white matter integrity (fractional anisotropy) in controls (compared to spelling and reading impaired children), whereas no structural differences between controls and spelling impaired children were observed.

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1. Introduction

Depending on definition and stringency of criteria used, approximately 3–15% of children show difficulties in reading and spelling (Eden & Zeffiro, 1998; Gabrieli, 2009; Habib, 2000; Shaywitz et al., 2003) that may be associated with a greater risk of school anxiety, unemployment and multiple emotional and behavioral difficulties (Arnold et al., 2005; Daniel et al., 2006; Fluss et al., 2009; Ise & Schulte-Körne, 2010; Klicpera, Schabmann, & Gasteiger-Klicpera, 2007; Maughan, Rowe, Loeber, & Stouthamer-Loeber, 2003; Morgan, Farkas, Tufis, & Sperling, 2008). To date, numerous studies investigated behavioral and brain processes involved in reading impaired individuals (e.g. Eden, Brown, Jones, Given, & Zeffiro, 2000; Meyler et al., 2007; Richlan et al., 2010; Shaywitz et al., 2007) and frequently imply that spelling impairment is only

a secondary phenomenon. Only few studies focused on spelling impairment itself (e.g. Richards, Berninger, & Fayol, 2009). Nevertheless, deficits frequently go beyond reading and it is important to achieve a better understanding of common neuropsychological deficits besides reading ability. Although spelling difficulties are associated with dyslexia they have been largely neglected by the majority of studies in this field (Angelelli, Notarnicola, Judica, Zoccolotti, & Luzzatti, 2010).

Especially the English-speaking community focuses strongly on reading impairment. For instance, the DSM IV (APA, 1994) contains a diagnosis of isolated “reading disorder” (315.00), but no diagnosis for spelling impairment, instead containing the “disorder of written expression” (315.2). In more transparent orthographies such as Spanish, Finnish, Italian, Greek, reading accuracy is hardly affected, whereas impairments of reading speed and severe and persistent impairments in spelling are observed (Wimmer, Mayringer, & Landerl, 1998). Accordingly, in the ICD 10 (Dilling, Mombour, & Schmidt, 2005), which is the major diagnostic manual used in German speaking countries, an isolated impairment is only assumed for spelling (F 81.1), whereas for reading disorder (F 81.0) associated spelling problems are supposed to be frequent and mainly

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secondary to reading difficulties. It was also found that children with isolated spelling difficulties show different patterns of cognitive deficits compared to children with both reading and spelling difficulties (Moll & Landerl, 2009; Wimmer & Schurz, 2010). Isolated spelling difficulties in German-speaking samples were found in about 3–6% (Moll & Landerl, 2009; Wimmer & Mayringer, 2002). Due to the transparent orthography in German, dyslexics manage to read slow but accurate in the course of their development, whereas spelling mistakes rather persist into adulthood (Landerl & Klicpera, 2009). Interestingly, Moll and Landerl (2009) found that children with isolated spelling deficits named pseudohomophones as quickly as their corresponding words, and that their phonological awareness skills were adequate. The authors suggested that the reading in children with isolated spelling deficits may be based on highly efficient grapheme-phoneme decoding procedures. Due to the asymmetry in German language (grapheme-phoneme correspondence is high, but phoneme-grapheme correspondence is low) this strategy is not helpful for spelling difficulties, as different spellings for words with the same pronunciation (e.g. *Wal/whale* – *Wahl/election*) exist.

Another explanation could be that deficits in vowel length perception might be responsible for spelling disorders. In German orthography vowel length is not marked by the vowel letter itself, but by the letters following the vowel. Short vowels are, often marked by two following consonants (e.g. *Stall*, /\$tal/, [barn]), whereas for a long vowel frequently a “silent h” (e.g. *Stahl*, /\$ta:l/, [steel]) is added (Groth, Lachmann, Riecker, Muthmann, & Steinbrink, 2011). Difficulties in perceiving these differences in vowel length might impair spelling ability.

Based on these considerations we speculated that the functional patterns of brain activity should dissociate between children with isolated spelling impairment and children with deficits in reading and spelling. Several theories about deficits underlying spelling and reading impairment emerged from behavioral and neuroimaging studies (e.g. phonological deficit theory, see further Ramus et al., 2003; magnocellular deficit theory, Stein, 2001; double-deficit theory, Wolf & Bowers, 1999; cerebellar deficit theory, Nicolson et al., 1999; temporal processing theory, Steinbrink, Ackermann, Lachmann, & Riecker, 2009). Heterogeneous patterns of brain activation differences in cortical and subcortical regions between children and adults with difficulties in reading and spelling and non-impaired controls were found across studies. Frequently, a lower activation in parieto-temporal and occipito-temporal brain regions of the left hemisphere, associated with deficits in reading-related skills, such as grapheme-phoneme-conversion and automatic and fluent reading (Kronbichler et al., 2008; Shaywitz et al., 2004) is mentioned to be related to dyslexia. In addition, dyslexics often show increased frontal and right hemispheric activation, which is thought to be related to compensatory activity, e.g. internal articulation (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Richlan, Kronbichler, & Wimmer, 2009; Shaywitz, Mody, & Shaywitz, 2006). Recent research on reading difficulties found substantial support that left occipito-temporal reading circuits (comprising the visual word form area; see further Dehaene & Cohen, 2011) are the origin of persistent impairments of fast fluent reading (e.g. Cohen et al., 2000; Kronbichler et al., 2006), but so far only little is known about the neural substrate of spelling (Hillis et al., 2002) and even less about underlying brain mechanisms of spelling difficulties.

For a long time, the left angular gyrus (and left supramarginal gyrus) was assumed to play a critical role in spelling (Booth et al., 2002, 2004; Roeltgen, 1993; Rapcsak & Beeson, 2002). Other studies rather suggest that the left posterior temporal lobe (BA 37; Petrides, Alivisatos, & Evans, 1995), especially the inferior region (Beeson, Rapcsak, Plante, Chargualaf, Chung, & Johnson, 2003; Rapcsak & Beeson, 2004) is associated with spelling. Rapp and

colleagues (Rapp & Lipka, 2011; Tsapkini & Rapp, 2010) propose the left mid-fusiform region to be related to spelling. Purcell, Napoliello, and Eden (2011) state that perisylvian regions including the inferior frontal gyrus and supramarginal gyrus seem to play a significant role of phoneme-grapheme mapping in spelling (see also Katanoda, Yoshikawa, & Sugishita, 2001; Rapp & Lipka, 2011; Sugihara, Kaminaga, & Sugishita, 2006). Richards et al. (2009) conducted a study with poor spellers and found a stronger activation of the bilateral precuneus, posterior cingulum and frontal regions, probably reflecting inefficient neural mechanisms and increased effort compared to controls.

Several studies using diffusion tensor imaging (DTI) found a correlation between white matter integrity (mostly measured by fractional anisotropy, FA) and reading ability in the left parieto-temporal area (e.g. Beaulieu, Plewes, Paulson, Roy, Snook, & Concha, 2005; Deutsch et al., 2005; Klingberg et al., 2000; Niogi & McCandliss, 2006). To our knowledge only two DTI studies included behavioral measures of spelling. Deutsch et al. (2005) found positive correlations between measurements of reading ($r=.62$) and spelling ($r=.66$) with left parieto-temporal connectivity in children with reading and spelling impairment. Suggesting that better white matter integrity in this region is related to a general improved processing efficiency. Steinbrink et al. (2008) investigated German dyslexic adults and found a decreased FA in bilateral fronto-temporal and left temporo-parietal white matter regions, probably indicating less efficient communication in dyslexics. No significant correlations with spelling were reported, but a significant correlation between FA and reading speed.

In a previous study (Gebauer et al., submitted for publication) we examined the effects of spelling intervention on children with spelling and reading impairment, investigating a training group and a waiting group (each group included children with isolated spelling impairment and reading and spelling impairment) by means of repeated behavioral assessment, functional MRI and DTI. We here addressed the central research question whether functional and structural patterns of brain activity in children with isolated spelling impairments differ from those observed in children with impairments in reading and spelling and in healthy controls. We hypothesized that (a) children with poor spelling and reading abilities might show a reduced activation of the left occipito-temporal region compared to controls. We further presumed that (b) children with isolated spelling difficulties might possibly show reduced brain activation in the left angular gyrus or posterior inferior temporal cortex, accompanied with an increased activation in the homolog right hemispheric areas. We further expected (c) decreased white matter integrity (FA) in children with spelling and reading impairment in the left parieto-temporal cortex.

2. Methods

2.1. Participants

Out of 107 subjects, 42 German-speaking children aged between 9 and 15 years were recruited based on a behavioral pre-screening. Standardized tests for the assessment of reading and spelling abilities were administered, and information on relevant socio-demographic data such as age, sex, native language and school year was recorded.

To assess spelling skills, we used the Hamburger-Schreibprobe (HSP; May, Vieluf, & Malitzky, 2000), a standardized spelling test. In the HSP, words and sentences are dictated by the experimenter and have to be written next to the corresponding pictures that illustrate the respective words or sentences. This test takes about 15 min and within this study the version for 4th/5th graders and 5th–9th graders were applied. The HSP provides measures for the number of correctly spelled words and the number of grapheme-related mistakes. The latter was used in this study as it provides a more precise measure of spelling ability.

Additionally, we measured reading speed and basic reading ability (automaticity, accuracy), by means of the Salzburger-Lese-Screening (SLS; Mayringer & Wimmer, 2003, 2005). The SLS 1–4 was used for children up to the 4th grade, and the SLS-5–8 was applied for older children, parallel versions exist for both. In the

Table 1

Descriptive statistics of age, non-verbal intelligence, reading speed, reading comprehension and spelling skills and behavioral performance inside the scanner: correctly solved items in percent and reaction time (RT). Means and standard deviations (in brackets).

	SI	SRI	CG	p
Age (years)	11.73 (±1.6)	11.33 (±0.7)	12.27 (±1.9)	.41
Intelligence – Raven	37.2 (±8.4)	35.9 (±8.5)	42.8 (±5.5)	.10
Spelling skill – HSP	22.4 (±10.9)	20.3 (±12.2)	74.0 (±15.1)	.00
Reading speed – SLS	103.1 (±9.7)	84.1 (±6.0)	115.1 (±14.3)	.00
Reading comprehension – ELFE	53.2 (±7.8)	45.1 (±3.6)	61.2 (±8.3)	.00
Correctly solved %	72.24 (±9.16)	70.81 (±9.41)	89.53 (±5.62)	.00
Reaction time	1.31 (±0.18)	1.37 (±0.28)	1.34 (±0.20)	.83

Age ($F_{(2,28)} = 0.92$; $p = 0.41$; $\eta^2 = .06$), non-verbal intelligence: Raven raw scores ($F_{(2,28)} = 2.50$; $p = 0.10$; $\eta^2 = .15$); spelling skills: HSP percent range ($F_{(2,28)} = 59.17$; $p < .001$; $\eta^2 = .81$); reading speed: SLS reading quotient ($F_{(2,28)} = 20.38$; $p < .001$; $\eta^2 = .59$). Reading comprehension: ELFE T -scores ($F_{(2,28)} = 12.77$; $p < .001$; $\eta^2 = .48$). Correctly solved: $F_{(2,28)} = 17.21$; $p < .001$; $\eta^2 = .55$. RT: $F_{(2,28)} = p > .05$; $\eta^2 = .01$.

SLS, children have to decide whether the content of a presented sentence is correct or not. Testing time is limited to 3 min.

In addition we measured reading comprehension (i.e. comprehension of words, sentences and text) by means of a standardized “German-speaking test” (ELFE 1–6; Lenhard & Schneider, 2006). Furthermore, non-verbal intelligence was measured by means of the Standard Progressive Matrices (SPM) by Raven (1960). We also assessed personality by means of the Five-Factor-Questionnaire for children by Asendorpf (1998) to control for potential influences of specific traits on performance. However, no differences between the groups were observed. Hence, we did not further include personality factors.

Only participants with less than 3 mm motion and less than 1 mm motion between sequential functional volumes were included in the analysis. Eleven children had to be excluded due to movement artifacts ($n = 7$), poor behavioral performance inside the scanner ($n = 2$, Mean Accuracy < 50%) or because they decided to terminate the fMRI session ($n = 2$), rendering a final sample of 31 children¹ (15 males) in the age between ten and 15 years ($M = 11.81$; $SD = 1.56$). All participants were healthy, right-handed and had normal or corrected-to normal vision. Structural brain scans were reported as normal in all children. The study was approved by the ethics committee of the Medical University of Graz, Austria. All participants and their parents gave written informed consent.

In a previous study (Gebauer et al., submitted for publication) we investigated the effects of spelling intervention on children with spelling and reading impairment. We here examined whether functional and structural patterns of brain activity in children with isolated spelling impairments differ from those observed in children with impairments in reading and spelling and in healthy controls. Therefore, we divided the children into three groups: (1) Eleven children with isolated spelling impairment (SI) and (2) nine spelling and reading impaired children (SRI), as it was determined by means of standardized psychometric tests for the assessment of reading and spelling abilities. Furthermore (3), a control group consisting of 11 children (CG) was investigated. We analyzed the functional MRI and DTI data in order to address the central research question whether functional and structural patterns of brain activity in children with isolated spelling impairments differ from those observed in children with impairments in reading and spelling and in healthy controls.

Children in the spelling impaired (SI) group showed poor spelling skills (spelling scores one to two standard deviations below average) along with average reading skills, whereas children in the SRI group showed impairments in spelling and reading (spelling and reading scores one to two standard deviations below average). Controls had significantly higher spelling scores than both impaired groups ($p < .05$; see Table 1), while the comparison between the SI and the SRI were not significant.² Furthermore, controls had significantly higher reading speed scores than both impaired groups. The spelling impaired (SI) group had significantly higher reading speed scores compared to the SRI group ($p < .05$; see Table 1). The same pattern was found for reading comprehension ($p < .05$; see Table 1). The groups did not differ with respect to age and non-verbal intelligence ($p > .05$; see Table 1).

2.2. Functional MRI (fMRI) experimental stimuli and tasks

Three different orthographic decision conditions were presented during event-related fMRI (1: correctly spelled words, 2: misspelled words, 3: pseudowords). Similarly to the spelling judgment task of Richards et al. (2009), children had to decide whether a presented word was spelled correctly (e.g. Bäume; trees), incorrectly (e.g. fergesslich instead of vergesslich; forgetfull instead of forgetful) or if it is a pseudoword (e.g. Ostablast). The correct decision for misspelled versus correctly spelled words requires orthographic processing, as the misspelled words are phonologically correct, resembling the pseudohomophones (see Kronbichler et al., 2007; Van der Mark et al., 2009). Answers were given via button press of the right

hand, with the index finger for correctly spelled, real words and the middle finger for misspelled or pseudowords and were recorded in a log-file (see Fig. 1). Behavioral responses inside the scanner were assessed in order to control the percentage of correct reactions across tasks. Furthermore, a fixation cross was presented as a baseline, where no button press was required. A familiarization task outside the scanner was obtained to ensure that the instruction was understood properly. Each condition consisted of 75 items, which were equal according to length and word type (25 nouns, 25 verbs, 25 adjectives).

Items and fixation were presented in randomized order for 3 s. The order of items and fixations was optimized by a genetic algorithm for hemodynamic response detection (Wager & Nichols, 2003). This approach helps to find the optimal sequence of events in event-related fMRI in order to maximize statistical power and psychological validity. The total time of the fMRI experiment was 16 min and the entire MRI session took 30 min.

2.3. Magnetic resonance imaging (MRI) data acquisition

Imaging was performed on a 3.0 T Trio Tim scanner (Siemens Medical Systems, Erlangen, Germany) using a 12-channel head coil. To minimize head movement, subjects' heads were stabilized with foam cushions. A high resolution (1 mm × 1 mm × 1 mm) structural scan (TR = 1900 ms, TE = 2.2 ms) was acquired to allow precise registration of functional data to individual anatomy. Structural brain scans were reviewed by an expert and did not show morphological abnormalities. Furthermore, diffusion tensor imaging (2 mm × 2 mm × 2.5 mm, TR = 6700 ms, TE = 95 ms, FOV = 250 mm, FA: 90°) data were obtained. Functional images were acquired with a single-shot gradient echo EPI sequence (TR = 2190 ms, TE = 30 ms, FOV = 192 mm, FA = 90°, 36 3 mm thick slices). Visual stimuli were synchronized with the MR-scanner using the Software Presentation (Neurobehavioral Systems, Albany, CA) and back-projected onto a translucent plastic screen which was installed on the roof of the scanner bore. Participants watched the screen through a mirror attached on the top of the head coil. Answers were given via button response box as described above.

2.3.1. Behavioral data analyses

Task performance during fMRI recording (accuracy and reaction time of responding to the experimental spelling tasks), was assessed by means of univariate ANOVA's, using the Tukey HSD test for post hoc comparisons (PASW 18).

2.3.2. Functional magnetic resonance imaging (fMRI) data analyses

Functional MRI data analysis was performed using FEAT (fMRI Expert Analysis Tool; Version 4.1.5, part of FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). The following preprocessing steps were applied: motion correction using MCFLIRT; high-pass filter cut-off 100 s; non-brain removal using BET; interleaved slice time correction; spatial smoothing using a Gaussian kernel of 6 mm FWHM; and high-pass temporal filtering. Time series statistical analysis was carried out using FILM. The motion parameters were included in the model as covariates of no interest. Nonlinear registration to high-resolution and standard images (Montreal Neurological Institute (MNI) space) was carried out using FNIRT. Higher level analysis was done using FLAME (FMRIB's Local Analysis of Mixed Effects). If not otherwise specified, Z statistic images were thresholded using clusters determined by $Z > 2.3$ and a corrected cluster significance threshold of $p = 0.05$ (using Gaussian Random Field Theory).

Analyses for the entire group were performed by computing linear t -contrasts between selected experimental conditions for the orthographic decision task for each participant individually, which were then entered into a random effects two sample t -test. For a detailed overview of the FSL design matrix see Fig. A.1 in appendix.

According to our findings and theoretical background we computed five functional regions of interest (ROI) in the right supramarginal gyrus (SMG), right superior parietal lobe (SPL), right inferior frontal gyrus (triangularis), the medial frontal gyrus and the left occipito-temporal (OT) region. ROI analyses were computed using FEAT-QUERY and PASW 18 (computing ANOVA's along with Tukey HSD test for post hoc comparisons; see Fig. 4).

¹ Children participating in this study were investigated in another research context; see Gebauer et al. (submitted for publication).

² Revealed by specific post hoc comparison by means of the Tukey HSD test.

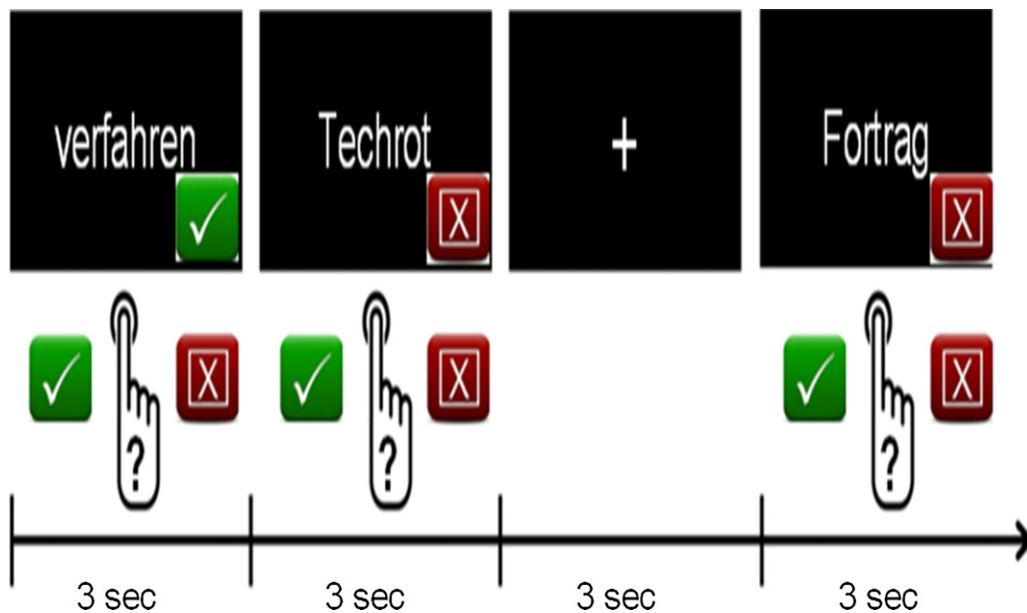


Fig. 1. Overview of experimental design and measurement intervals. Correctly spelled words, misspelled words, pseudowords and a fixation cross were presented in a randomized order for 3 s. In each orthographic decision condition participants were instructed to respond, by pressing either the “correct” button with the index finger [verfahren = to proceed] or the “misspelled/pseudoword” button with the middle finger on the response console [Techrot, Fortrag = lecture]. The responses were given with the right hand and recorded and logged for further analyses.

2.3.3. Diffusion tensor imaging (DTI) data analyses

Diffusion tensor imaging (DTI) analysis was performed using FDT (fMRIB's Diffusion Toolbox, Version v 2.0, part of fMRIB's Software Library) and TBSS (Tract-Based Spatial Statistics, Version v 1.2, part of fMRIB's Software Library).

Raw images were pre-processed using eddy current correction. A brain mask was created using BET (Brain Extraction Tool, Version 2.1). Maps for fractional anisotropy (FA), were generated using DTIFit (FDT). Subsequently voxelwise statistical analysis of the FA data was carried out using TBSS. Because standard templates do not appear appropriate for the smaller head and brain size of children, a study-specific template was generated by registering the FA images to the mean_FA of the group (created with the FMRIB58_FA image as the target). The FA skeleton was thresholded at 0.20, to include major white matter pathways but avoid peripheral tracts (vulnerable to intersubject variability; see Fig. A.2 in appendix). Each subjects FA was then projected onto the mean skeleton. Voxel-wise cross-subject statistics (TFCE thresholding, $p < .05$) using nonparametric testing as implemented in “randomize” (5000 permutations), calculating group contrasts was applied. The anatomical location of the significant clusters was determined by reference to the fiber tract-based atlas of human WM (JHU ICBM-DTI-81 White-Matter Labels, JHU White-Matter Tractography Atlas, Juelich Histological Atlas), implemented at FSL.

3. Results

3.1. Behavioral performance inside the scanner

In order to investigate task performance during fMRI recording (as it was measured by means of accuracy and reaction time of responding to the experimental spelling tasks), the ANOVA yielded a significant GROUP effect. Post hoc comparisons revealed that the controls reached significantly higher percentage of correctly solved words than both impaired groups during the fMRI session. The spelling impaired (SI) group and spelling and reading impaired (SRI) group did not differ significantly ($p < .001$; see Table 1). No differences in reaction time were found between groups ($p > .05$; see Table 1).

3.2. Functional MRI results

3.2.1. Contrasts between experimental conditions

In all three groups processing of the orthographic decision tasks (1: correctly spelled words; 2: misspelled words; 3: pseudowords) elicited activation in left pre- and postcentral gyrus (button press) and large areas in the occipital and occipito-temporal cortex of

both hemispheres (visual input), relative to rest. The judgment of correctly spelled words evoked additional activation in the left inferior frontal gyrus (IFG) in all three groups, and an additional activation of the right IFG in the spelling impaired group (SI). The condition misspelled words caused activation in the right inferior frontal gyrus in all three groups (see Fig. 2). For a more detailed overview of activation clusters and local maxima see Table A.1 in appendix.

3.2.2. Contrast between groups

3.2.2.1. Increased activation for children with SI (compared to SRI and controls). The condition misspelled words was associated with more activation in the SI group in the right hemisphere compared to the SRI and control group. More specifically, this concerned the superior parietal lobule, the supramarginal gyrus (SMG) and the parietal operculum compared to children with SRI and the frontal medial, subcallosal and paracingulate cortex compared to controls. Furthermore, increased activation in the left superior parietal lobe compared to the SRI group was found.

The pseudoword condition elicited increased activation in the right frontal operculum and frontal pole compared to controls (see Fig. 3). For a more detailed overview of activation clusters and local maxima see Table A.2 in appendix ($Z > 1.8$; $p = .05$). Only significant comparisons are reported.

3.2.2.2. Increased activation for the CG compared to SRI. Increased activation for controls compared to the SRI group in the right hemisphere (cuneus and lateral occipital) was found during all conditions. In addition, the condition misspelled words caused stronger activation in the right precuneus and cerebellum. The pseudoword condition led to a stronger activation in the left occipito-temporal fusiform gyrus, inferior temporal gyrus and right cerebellum in controls. No stronger activation of the CG compared to SI children was found. Only significant comparisons are reported.

3.2.3. Region of interest (ROI) analyses

According to our findings and theoretical background we computed five ROI analyses, including the right supramarginal gyrus

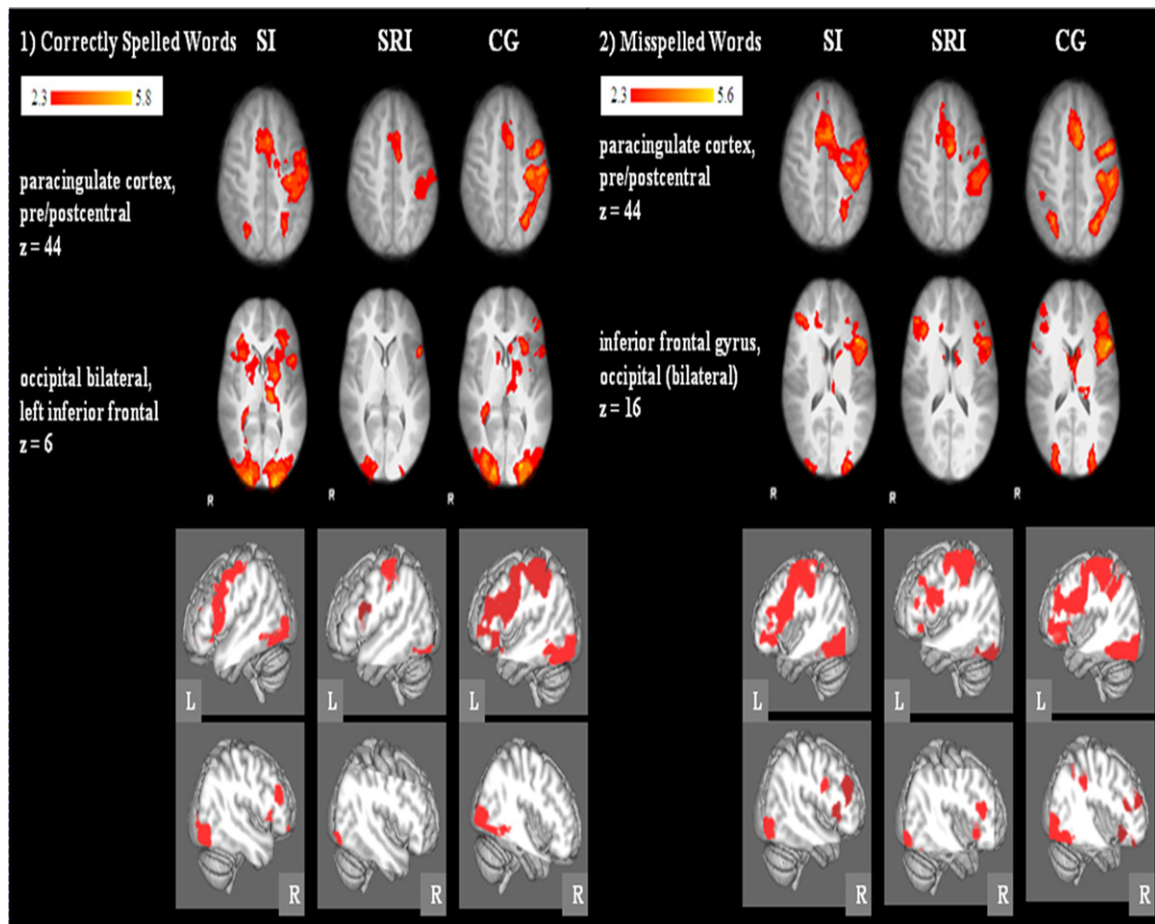


Fig. 2. Mean activation of spelling impaired children (SI), children with spelling and reading impairments (SRI) and controls (CG) for correctly spelled words and misspelled words ($Z > 2.3$; P corrected; $P = 0.05$).

(SMG), right superior parietal lobe (SPL), right inferior frontal gyrus (triangularis), medial frontal gyrus and the left occipito-temporal (OT) region.

3.2.3.1. Right supramarginal gyrus (SMG). The right supramarginal gyrus (SMG), yielded a significant GROUP effect ($F_{(2,28)} = 3.72$; $p < .05$; $\eta^2 = .21$) when correctly spelled words were processed. Post hoc comparisons revealed that children with spelling impairment (SI) showed increased activation of the right SMG compared to children with spelling and reading impairment (SRI). Also

during processing misspelled words a significant GROUP effect ($F_{(2,28)} = 7.55$; $p < .05$; $\eta^2 = .35$) emerged. Post hoc comparisons revealed increased activation for SI compared to controls and SRI (see Table 2 and Fig. 4). No significant group effect was found for the condition pseudowords.

3.2.3.2. Right superior parietal lobe (SPL). Significant GROUP effects were found during all orthographic decision tasks (Correct: $F_{(2,28)} = 4.30$; $p < .05$; $\eta^2 = .24$; Misspelled: $F_{(2,28)} = 4.39$; $p < .05$; $\eta^2 = .24$; Pseudowords: $F_{(2,28)} = 4.83$; $p < .05$; $\eta^2 = .26$). Post hoc

Table 2

ROI – results of univariate ANOVAs for correctly spelled words (C), misspelled words (M) and pseudowords (P). Means and standard deviations (in brackets).

		SI	SRI	CG	<i>p</i>
Right SMG	C	−0.18 (0.18)*	−0.49 (0.34)	−0.33 (0.23)	.037
	M	−0.22 (0.20)*	−0.60 (0.21)	−0.48 (0.24)	.002
	P	−0.29 (0.20)	−0.51 (0.26)	−0.40 (0.23)	.104
Right SPL	C	−0.02 (0.20)*	−0.40 (0.41)	−0.12 (0.25)	.023
	M	−0.04 (0.25)*	−0.38 (0.25)	−0.08 (0.31)	.022
	P	−0.05 (0.18)*	−0.34 (0.30)	−0.14 (0.26)	.016
Medial Frontal	C	−0.11 (0.26)	−0.36 (0.59)	−0.27 (0.40)	.277
	M	−0.30 (0.15)	−0.37 (0.50)	−0.72 (0.24)*	.011
	P	−0.20 (0.24)	−0.22 (0.52)	−0.23 (0.35)	.844
Left OT	C	0.22 (0.20)	0.04 (0.26)	0.51 (0.27)**	.001
	M	0.25 (0.26)	0.04 (0.18)	0.60 (0.41)**	.001
	P	0.14 (0.16)	−0.10 (0.24)	0.47 (0.27)**	.000

Explanation of abbreviations: SMG, supramarginal gyrus; SPL, superior parietal lobe; OT, occipito-temporal region.

* $p < .05$ (two-tailed).

** $p < .001$ (two-tailed).

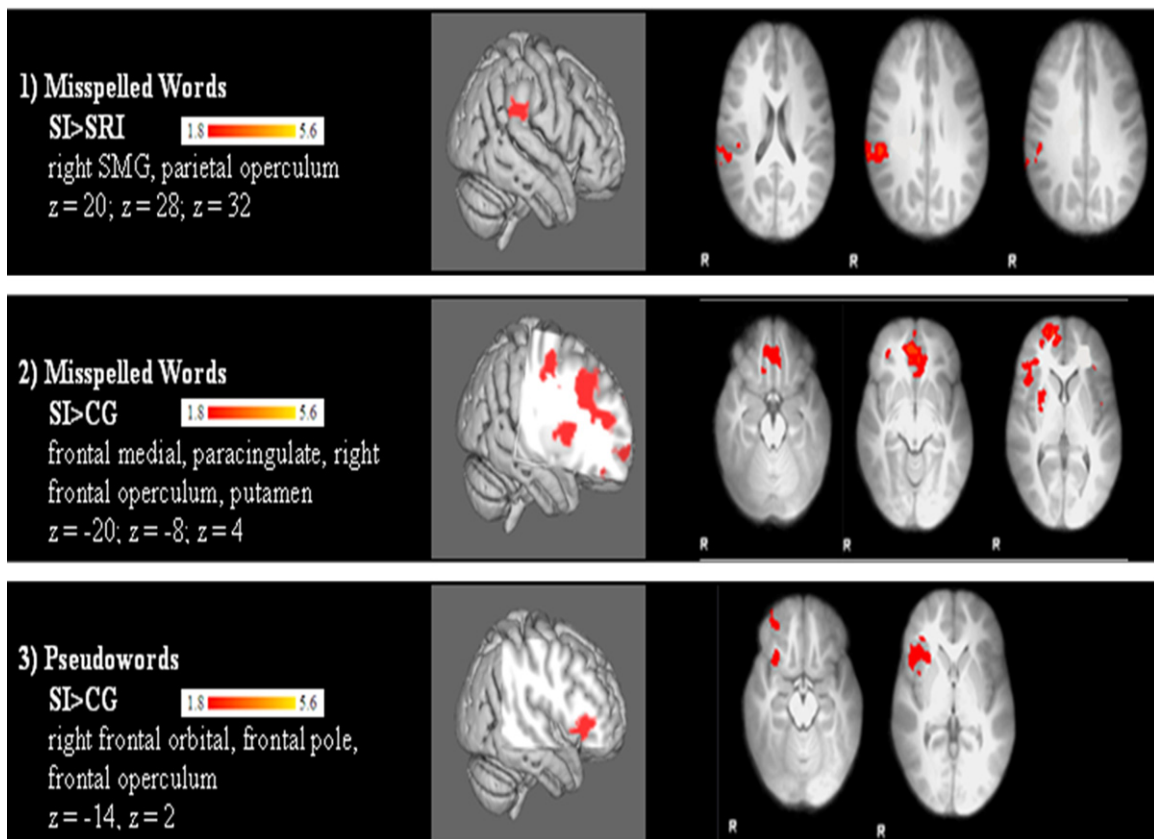


Fig. 3. Increased activation during the processing of misspelled words for the (1) spelling impaired (SI) children compared to children with spelling and reading impairment (SRI) and (2) compared to controls (CG). (3) Stronger activation during the processing of pseudowords for SI compared to CG ($Z > 1.8$; P corrected; $P = 0.05$).

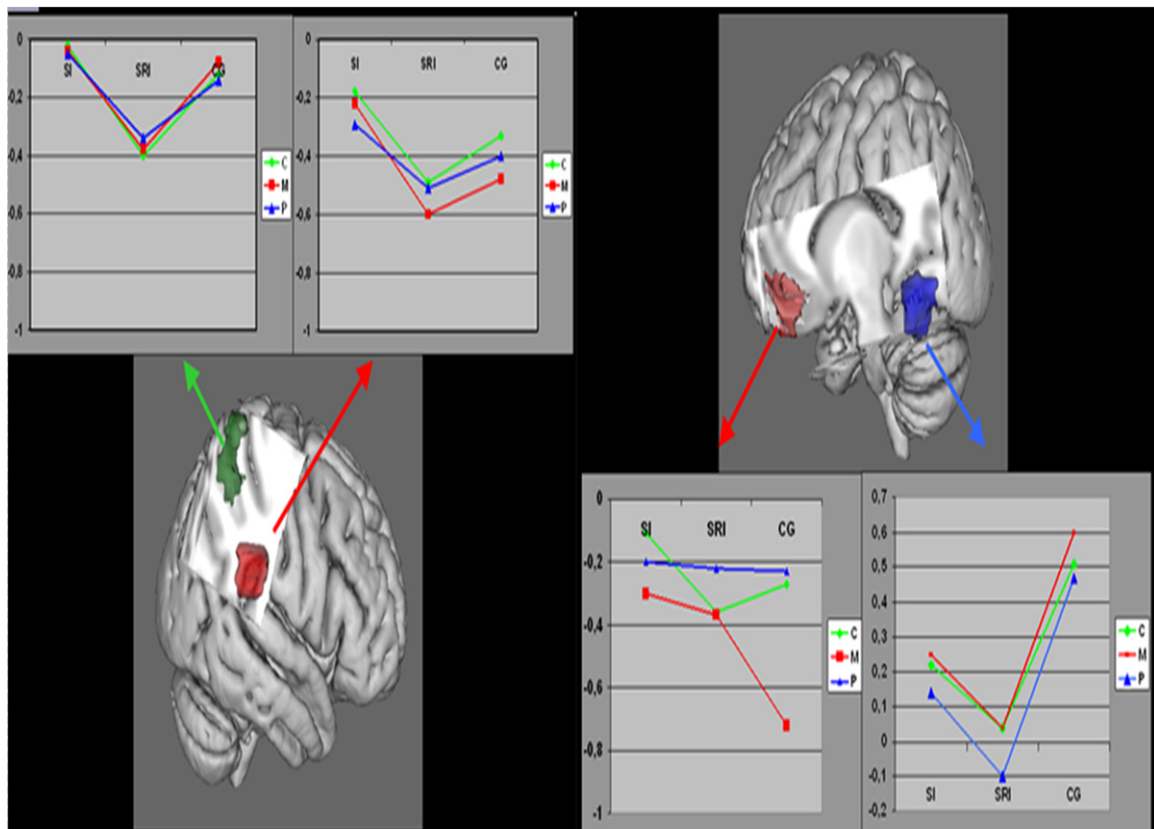


Fig. 4. ROI with significant GROUP effect. Above = right superior parietal lobe and right supramarginal gyrus. Below = medial frontal gyrus and left occipito-temporal region. correctly spelled words (C), misspelled words (M) and pseudowords (P).

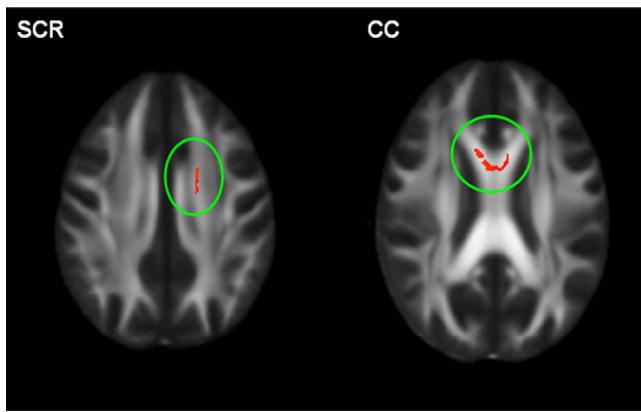


Fig. 5. Differences in white matter integrity (FA) between CG and SRI, in the left anterior superior corona radiate (SCR) and anterior corpus callosum (CC).

comparisons revealed increased activation for spelling impaired children (SI) compared to SRI when correctly spelled words were presented and increased activation for SI children and controls compared to SRI when misspelled words or pseudowords were presented (see Table 2 and Fig. 4).

3.2.3.3. Right inferior frontal gyrus (IFG). For the right IFG no significant GROUP effects were observed.

3.2.3.4. Medial frontal gyrus. A significant GROUP effect for the medial frontal gyrus was observed ($F_{(2,28)} = 5.38$; $p < .05$; $\eta^2 = .28$) when misspelled words were presented. Post hoc comparisons revealed decreased activation for controls compared to spelling impaired children (SI) and tentatively decreased activation of controls compared to SRI ($p = .056$; see further Table 2 and Fig. 4).

3.2.3.5. Left occipito-temporal (OT) region. A significant GROUP effect for the left occipito-temporal region was observed (Correct: $F_{(2,28)} = 9.48$; $p < .001$; $\eta^2 = .40$; Misspelled: $F_{(2,28)} = 8.67$; $p < .001$; $\eta^2 = .38$; Pseudowords: $F_{(2,28)} = 15.93$; $p < .001$; $\eta^2 = .53$). Post hoc comparisons revealed increased activation of the left OT region in controls, compared to the impaired groups (see Table 2 and Fig. 4).

3.3. DTI results

DTI analyses revealed higher fractional anisotropy (FA) in controls (compared to SRI) in the left anterior superior coronar radiata (SCR) and anterior corpus callosum (see Fig. 5). No differences between the two impaired groups in FA were observed. No difference between controls and children with isolated spelling impairment (SI) were observed.

4. Discussion

This study investigates for the first time patterns of brain activity in spelling impaired children (SI) in comparison to children with spelling and reading impairment (SRI) and controls. As a major finding, children with isolated spelling impairment showed a stronger right hemispheric activation during processing orthographic decision tasks compared to children with SRI and controls. This could reflect a compensatory mechanism, allowing German-speaking children with isolated spelling deficits to avoid reading deficits by gaining word specific knowledge through intact serial grapheme-phoneme decoding (Moll & Landerl, 2009). This compensatory mechanism is successful for the compensation of reading deficits, whereas spelling impairments remain, because of the asymmetry in German language (grapheme-phoneme correspondence is

high, but phoneme-grapheme correspondence is low). Equal word spellings with different pronunciations (e.g. English *the wind – to wind*) do not exist in German, whereas different spellings for words with the same pronunciation are common (e.g. *Wal/whale – Wahl/election*). Hence, it is not possible to derive the correct spelling by this serial phoneme-grapheme decoding strategy.

In line with this assumption, region of interest analyses revealed increased activation in right posterior areas (SMG and SPL) related to grapheme-phoneme conversion (Booth et al., 2002, 2004), attention (Peyrin, Démonet, Guyen-Morel, Le Bas, & Valdois, 2010) and working memory (Berryhill & Olson, 2008; Koenigs, Barbey, Postle, & Grafman, 2009), in spelling impaired children. Hoefft et al. (2011) found that dyslexic children who relied on right hemispheric pathways showed gains in reading. This further supports our theory that the stronger right hemispheric engagement of spelling impaired children may reflect a compensatory mechanism, related to adjustment of reading skills. The activation of superior parietal regions could indicate increased attentional and working memory effort in this group in order to overcome dysfunctions.

In addition (comparing mean activation maps of the groups), children with spelling impairment activated bilateral inferior and middle frontal gyri during processing correctly spelled words and misspelled words, whereas the other two groups showed left frontal activation for the correctly spelled words and bilateral activation only in the misspelled condition. Increased activation of the left and right inferior frontal gyri (IFG) has often been interpreted as a compensatory process of dyslexics in order to overcome dysfunctions in left posterior cortical areas subserving phonological and orthographic processing (Hoefft et al., 2011). We found an increased right frontal engagement in spelling impaired children compared to controls, although surprisingly not in the IFG (triangularis) but in adjacent regions (frontal orbital region, frontal pole). The right IFG engagement occurred in all three groups in the more difficult condition (misspelled words). Probably this additional bilateral IFG engagement is reflecting a more general increase of activation because of higher task demand, apparent in impaired children and non-impaired children. Nevertheless, we found increased additional activation in the frontal medial region, related to more effortful and attentionally guided reading strategy (Meyler, Keller, Cherkassky, Gabrieli, & Just, 2008) for both impaired groups.

According to the current literature (Kronbichler et al., 2006; Richlan et al., 2009; Schurz et al., 2010), children with difficulties in spelling and reading (SRI) exhibit decreased cortical activation during orthographic decision tasks in left occipito-temporal (OT) regions compared to controls, most prominently during the presentation of pseudowords. A region of interest analyses revealed decreased activation of the left OT region for SI and SRI children, but with a higher extent for the SRI. Also, decreased occipito-parietal activation (relative to controls) in children with SRI was observed, probably indicating reduced serial guidance of visual attention (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Schurz et al., 2010). Increased activation of controls (relative to SRI) was observed in the precuneal and cuneal cortex, these regions are involved in attention, semantic processing and most notably with the default-mode network (Binder, Desai, Graves, & Conant, 2009; Cavanna & Trimble, 2006; Graves, Binder, Desai, Conant, & Seidenberg, 2010). Higher activation in this region is related to more self-referential thought and less task engagement. It seems that children with reading and spelling impairments had to concentrate more on the task.

Activation in non-impaired controls was observed in expected regions of reading network (e.g. occipital regions for visual processing, left occipito-temporal regions involved in visual word and letter string recognition, left temporo-parietal regions involved

in grapheme-phoneme computation and phonological word processing, left inferior frontal regions; see further Jobard, Crivello, & Tzourio-Mazoyer, 2003) and spelling network (e.g. left supra-marginal gyrus involved in mapping between orthography and phonology, left posterior temporal lobe related to an orthographic lexicon; see further Beeson et al., 2003; Booth et al., 2002, 2004; Rapcsak & Beeson, 2004).

DTI analyses revealed higher frontal white matter integrity (assessed by means of FA) in controls (compared to SRI) in the left anterior superior corona radiate (SCR) and anterior corpus callosum, probably indicating less efficient communication in children with SRI. Indications for a less efficient communication in bilateral fronto-temporal and left temporo-parietal white matter regions were also found in German dyslexic adults (Steinbrink et al., 2008), assuming that a disconnection syndrome of anterior and posterior regions involved in reading and spelling might be underlying dyslexia. No difference of left parieto-temporal white matter connectivity was found between our groups. Probably, differences in parieto-temporal white matter integrity emerge through inefficient use and are therefore not yet apparent in our young German-speaking sample. Nagy, Westerberg, and Klingberg (2004) also found correlations between frontal fractional anisotropy (FA) in the anterior corpus callosum and working memory capacity. Unfortunately, no working memory assessment was included in the present study, but it is likely that working memory (important for the process of reading) is affected in children with SRI. The SCR has been related to reading performance in children (e.g. Beaulieu et al., 2005; Deutsch et al., 2005), possibly explaining that differences were only observed for children with reading impairments. No evidence for differences in white matter integrity between children with spelling impairment compared to controls were found, supporting the theory of a functional compensatory mechanism, which probably induce also structural changes, in spelling impaired children.

5. Conclusion

We investigated whether or to which extent dissociations between spelling impaired children (SI) and children with spelling and reading impairments (SRI) exist in functional patterns of brain activity. It was found that children with isolated spelling difficulties show different patterns of brain activation compared to children with both reading and spelling difficulties. Our study suggests that spelling impaired children compensate for probably initially existent reading impairments by an increased recruitment of right posterior areas (SMG and SPL) related to grapheme-phoneme conversion, attention and working memory. DTI analyses revealed stronger frontal white matter integrity in controls, compared to spelling and reading impaired children, whereas no structural differences between controls and children with isolated spelling impairment were observed. This finding seems to support our theory of a functional compensatory mechanism, which probably induce also structural changes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuropsychologia.2012.02.020.

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