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Journal Article

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Publication date:
2024-03

Permanent link:
https://doi.org/10.3929/ethz-b-000660135

Originally published in:
Cortex 172, https://doi.org/10.1016/j.cortex.2023.12.010

CORTEX 172 (2024) 185–203

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Research Report

The odd one out – Orthographic oddball processing in children with poor versus typical reading skills in a fast periodic visual stimulation EEG paradigm

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ARTICLE INFO

Article history:
Received 17 March 2023
Reviewed 31 July 2023
Revised 17 September 2023
Accepted 12 December 2023
Action editor Joe Bathelt
Published online 17 January 2024

Keywords:
Visual print processing
Developmental dyslexia
FPVS oddball paradigm
EEG frequency-tagging
Steady-state visual evoked potentials (SSVEPs)

ABSTRACT

The specialization of left ventral occipitotemporal brain regions to automatically process word forms develops with reading acquisition and is diminished in children with poor reading skills (PR). Using a fast periodic visual oddball stimulation (FPVS) design during electroencephalography (EEG), we examined the level of sensitivity and familiarity to word form processing in ninety-two children in 2nd and 3rd grade with varying reading skills (n = 35 for PR, n = 40 for typical reading skills; TR).

To test children's level of "sensitivity", false font (FF) and consonant string (CS) oddballs were embedded in base presentations of word (W) stimuli. "Familiarity" was examined by presenting letter string oddballs with increasing familiarity (CS, pseudoword – PW, W) in FF base stimuli.

Overall, our results revealed stronger left-hemispheric coarse sensitivity effects ("FF in W" > "CS in W") in TR than in PR in both topographic and oddball frequency analyses. Further, children distinguished between orthographically legal and illegal ("W/PW in FF" > "CS in FF") but not yet between lexical and non-lexical ("W in FF" *vs* "PW in FF") word forms. Although both TR and PR exhibit visual sensitivity and can distinguish between orthographically legal and illegal letter strings, they still struggle with nuanced lexical distinctions. Moreover, the strength of sensitivity is linked to reading proficiency. Our work adds to established knowledge in the field to characterize the relationship between print tuning and reading skills and suggests differences in the developmental progress to automatically process word forms.

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https://doi.org/10.1016/j.cortex.2023.12.010

1. Introduction

Reading is a key communication skill in today's society and, consequently, learning to read is a crucial educational objective. Children become familiar with letters and script in early childhood due to their abundant presence in their everyday environment. Systematic instruction of the orthographic code and the link between spoken and written language usually starts with the beginning of reading acquisition at school enrollment. It is during this time that children's brains become sensitive to the visual appearance of letters and their combinations in words (Brem et al., 2010; Chyl et al., 2018; Dehaene-Lambertz, Monzalvo, & Dehaene, 2018; Maurer, Brem, Bucher, & Brandeis, 2005; Saygin et al., 2016). This sensitivity of the visual system is an important prerequisite for the efficient processing of written information. Coarse sensitivity to print is reflected in a differential neural response to processing letters and words in comparison to false font, symbol strings, or checkerboards as seen in studies using electroencephalography (EEG), magnetencephalography (MEG), or functional magnetic resonance imaging (fMRI) (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Brem et al., 2010; Cao, Li, Zhao, Lin, & Weng, 2011; Chyl et al., 2018; Maurer et al., 2006; Tong et al., 2016; Zhao et al., 2012). Rudimentary letter knowledge in kindergarteners or short grapheme–phoneme training is sufficient for the emergence of such an initial coarse print sensitivity, also sometimes referred to as coarse neural tuning for print/orthography or selectivity for letters (Coch & Meade, 2016; Eberhard-Moscicka, Jost, Raith, & Maurer, 2015; Maurer, Brandeis, & McCandliss, 2005; Wong, Gauthier, Woroch, Debuse, & Curran, 2005), in alphabetic languages (Brem et al., 2010; Cantlon, Pinel, Dehaene, & Pelphrey, 2011; Centanni, King, Eddy, Whitfield-Gabrieli, & Gabrieli, 2017; Dehaene-Lambertz et al., 2018; Karipidis et al., 2018; Maurer, Blau, Yoncheva, & McCandliss, 2010; Maurer, Brem, et al., 2005; McCandliss, Posner, & Givon, 1997; Pleisch et al., 2019; Yamada et al., 2011). Similarly, in logographic scripts such as Chinese, preschool children processed real characters differently from non-orthographic line- or radical combinations after a 25-min visual identification or writing training (Zhao, Zhao, Weng, & Li, 2018). With increasing practice and refinement of reading skills, the recognition of familiar words becomes fast and automatic and the neural response to words starts to differ from the response to nonwords or consonant strings as indexed by familiarity/lexicality effects (Bruno, Zumberge, Manis, Lu, & Goldman, 2008; Centanni et al., 2017; Eberhard-Moscicka et al., 2015; Tong et al., 2016). This distinction is sometimes referred to as fine neural tuning for words or the use of a fine-grained orthographic code (Adams, 1979; Coch & Meade, 2016; Cohen et al., 2002; Grainger & Holcomb, 2009; Maurer, Brandeis, et al., 2005; Zhao et al., 2014). Importantly, sensitivity and familiarity/lexicality effects can be detected even with tasks during which the stimuli are processed implicitly (Shtyrov, Goryainova, Tugin, Ossadtchi, & Shestakova, 2013).

Moreover, the typical development of reading coincides with a shift of neural responses to print to the left hemisphere (Gaillard, Balsamo, Ibrahim, Sachs, & Xu, 2003; Kershner, 2020; Maurer, Brem, et al., 2005; Maurer et al., 2010; McCandliss, Cohen, & Dehaene, 2003; Spironelli & Angrilli, 2009; Ventura, 2014), which is thought to occur due to an integration of new processes into the existing left-lateralized language network (Maurer & McCandliss, 2007; Sacchi & Laszlo, 2016): According to the Phonological Mapping Hypothesis, left-lateralized phonological processing drives the left-lateralization of print processing when grapheme–phoneme correspondences are trained (Maurer & McCandliss, 2007). Alternatively, the left-hemispheric specialization may emerge due to pre-established connections between frontal language and posterior visual areas (Saygin et al., 2016; Stevens, Kravitz, Peng, Tessler, & Martin, 2017).

Learning to read accurately and fluently does not come easy to all individuals, however. Individuals with developmental dyslexia (DYS) struggle to reach adequate reading levels despite adequate instruction and intelligence (APA, 2013; Démonet, Taylor, & Chaix, 2004; Lyon, Shaywitz, & Shaywitz, 2003; WHO, 2022). While phonological impairments are still considered a core deficit in DYS (Bonte & Blomert, 2004; Meyler & Breznitz, 2005; Snowling, 1998), the current view favors a multifactorial etiology rather than a single unifying deficit for DYS (O'Brien & Yeatman, 2021; Zuk et al., 2021). Accordingly, various studies have found differences in the neurobiology of visual word recognition in individuals with typical and poor reading skills across different developmental stages. A region within the left ventral occipitotemporal cortex (vOT) of the left hemisphere, the visual word form area (VWFA), was found to be crucial to reading (Cohen & Dehaene, 2004). In typically reading individuals, it becomes more activated upon the visual presentation of known orthographic stimuli (independent from variation in size, font, or case) (Cohen et al., 2000; Dehaene et al., 2004; McCandliss et al., 2003), compared to other visual stimuli (e.g., checkerboards, objects, or faces) (Centanni et al., 2017; Lerma-Usabiaga, Carreiras, & Paz-Alonso, 2018) and to unfamiliar letter- or letter-like stimuli (Brem et al., 2010; Bruno et al., 2008; Lerma-Usabiaga et al., 2018). The region is thought to have inherent properties (such as connections to the language network or responsivity to visual shape features (Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015; Li, Osher, Hansen, & Saygin, 2020; Saygin et al., 2016) that favor its specialization to reading upon instruction (Dehaene-Lambertz et al., 2018). Its further activity and connectivity development coincides with behavioral literacy advancement (Dehaene et al., 2010; Shaywitz et al., 2002). In experienced readers, the vOT cortex follows an anatomically graded posterior-anterior pattern of letter-, symbol-, and word

sensitivity suggesting a hierarchical processing of print (Brem et al., 2006; van der Mark et al., 2009; Vinckier et al., 2007). Converging functional and anatomical (structural connectivity and cytoarchitecture) evidence indicates the presence of at least two distinct subregions displaying word-selectivity. The posterior area being more involved in visual feature extraction and the anterior part in linguistic processing and relay (Caffarra, Karipidis, Yablonski, & Yeatman, 2021; Caffarra, Lizarazu, Molinaro, & Carreiras, 2021; Lerma-Usabiaga et al., 2018; White, Palmer, Boynton, & Yeatman, 2019). In individuals with poor reading skills, however, fMRI studies showed diminished print-related activation of the VWFA and a lack of the aforementioned posterior–anterior specialization pattern (Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999; Olulade, Flowers, Napoliello, & Eden, 2015; Paulesu et al., 2001; van der Mark et al., 2009; Wimmer & Schurz, 2010). Moreover, poor reading skills have been associated with decreased left-hemispheric occipitotemporal activation for orthographic processing and overactivation of the right hemisphere (Salmelin, Service, Kiesilä, Uutela, & Salonen, 1996; Shaywitz et al., 2002; Waldie, Haigh, Badzakova-Trajkov, Buckley, & Kirk, 2013; Weiss, Nárai, & Vidnyánszky, 2022), as well as changes in left-lateralized structural connectivity (Niogi & McCandliss, 2006; Zhao et al., 2023).

In event-related potential (ERP) studies using electroencephalography (EEG), the visual word N1 ERP (often also referred to as visual N170) reflects a correlate of VWFA activation, triggered by word- or letter-like stimuli (Allison, McCarthy, Nobre, Puce, & Belger, 1994; Brem et al., 2009; Maurer, Brem, et al., 2005; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). In individuals with typical reading skills, the N1 is stronger in response to letters or words compared to symbol string stimuli. This print-sensitive activation follows an inverted U-shaped trajectory across reading development: weak to non-existent in pre-readers, increased in beginning readers, and reduced again in expert readers (Brem et al., 2013; Fraga-González et al., 2021, 2022; Maurer et al., 2006; Yoncheva, Blau, Maurer, & McCandliss, 2010). As expertise increases, there is a transition from bilateral or right lateralization of the N1 to left lateralization (Maurer, Brem, et al., 2005; Tong et al., 2016; Uno, Kasai, & Seki, 2021). In children with DYS, this developmental progression as traced by the N1 appears to be altered (exhibiting an attenuated and less left-lateralized N1) (Araújo, Bramão, Faísca, Petersson, & Reis, 2012; Maurer, Wu, Mo, Wang, & Wang, 2020) or delayed (Fraga González, Žarić, Tijms, Bonte, & Van der Molen, 2017; Maurer et al., 2011).

An alternative approach to the N1 ERP time-domain paradigms involves applying frequency analysis to examine automatic familiarity processing in the visual domain using a fast periodic visual stimulation (FPVS) EEG paradigm (Lochy, Van Belle, & Rossion, 2015). In this kind of task, a specific stimulus type is presented at a certain periodic rate, which in response induces neuronal activity at the same frequency. Such periodically induced electrophysiological responses are referred to as steady-state visual evoked potentials (SSVEPs) (Montani, Chanoine, Stoianov, Grainger, & Ziegler, 2019). The FPVS oddball task displays a rapid sequence of base items that are periodically intermitted by oddball items. It thereby probes the sensitivity to implicitly discriminate between two classes of visual stimuli (Lochy et al., 2015) or even between stimuli of the same category but differing in their frequency of occurrence (De Rosa, Ktori, Vidal, Bottini, & Crepaldi, 2022). Applying frequency analysis, the periodicity of base and oddball stimulation (i.e., using different frequencies as identifiers for different stimulus categories; "frequency tagging") is exploited to test whether a neural response in relevant brain regions can be observed at the base and the oddball frequency bin in the EEG spectrum. While biological noise is scattered across the EEG bandwidth, the activities of interest are garnered at a single defined frequency each, rendering a high signal-to-noise ratio (SNR) within only a few minutes of stimulation time.

A seminal study in adults compared the visual presentation of W as oddballs with a frequency of 2 Hz embedded in false fonts (FF), nonwords (NW), or pseudowords (PW) as bases with a frequency of 10 Hz (Lochy et al., 2015). Left-lateralized discrimination responses were reported for all contrasts. In addition, responses were graded for similarity in that WinFF showed the largest discrimination signal, WinPW the weakest.

A recent study further examined oddball discrimination responses in adult readers in terms of the functional and temporal dynamics of response topographies (Wang et al., 2021). They found two sources with temporally separable time courses for WinFF contrasts (first left vOT, later dorsal parietal), in line with leading models of word processing (e.g. Long et al., 2020; Price & Devlin, 2011). However, they detected different sources for WinPW and WinNW, suggesting different underlying processes for word discrimination depending on the base context (Wang et al., 2021). Moreover, a recent study demonstrated that oddball responses have emerged across various visual categories based on the frequency of occurrence of items within a given category. This finding indicates implicit learning of statistical regularities in visual input streams, as highlighted by De Rosa et al. (2022).

To study automatic visual oddball responses in children, five-year-old pre-readers were studied using the contrasts WinFF, PWinFF, and WinPW with a 6 Hz base and 1.2 Hz oddball frequency (Lochy, Van Reybroeck, & Rossion, 2016). The results showed left-lateralized occipitotemporal responses to W or PW oddballs as compared with a midline occipital FF base response. In contrast to adults, however, the five-year-olds did not show a discrimination response for the WinPW contrast. These results suggest that pre-readers can automatically detect a difference between familiar and unfamiliar character strings, but not between real words and pseudowords. At odds with such previous findings, a recent study found lexical and sublexical tuning already in 7-year-old children, showing that the method of stimulation and analysis influences the detection threshold and that high-level linguistic processing occurs earlier than previously assumed (Wang et al., 2022).

In yet another FPVS study with first graders, W oddballs (in FF bases) were processed bilaterally if initially learned by a whole-word rote-learning approach ("globally taught words") in school. When, however, applying a phonics approach to teach the children word reading, W and PW oddball stimuli (in FF base) were processed predominantly in the left

hemisphere, which indicates grapheme–phoneme decoding (van de Walle de Ghelcke, Rossion, Schiltz, & Lochy, 2020b). Additionally, this hemispheric distinction for different teaching methods was modulated by reading skill: children with poor reading skills processed globally taught words more bilaterally than PW or W taught with phonics, while those with good reading skills activated the left hemisphere more strongly for all letter string stimuli. Based on these findings, the authors concluded that children with typical reading skills rely more on their automatized grapheme–phoneme mappings even for globally taught words, while those with poor reading skills applied the whole-word method. These results support the previously reported progressive left-lateralization with mastery of reading and specifically highlight the role of grapheme–phoneme conversion automaticity therein (e.g., Yoncheva et al., 2010). Moreover, they show that, indeed, the FPVS can be used to compare the processing of different oddball categories (e.g., different learning conditions) in addition to the processing of the classic oddball-base contrasts.

Here, we applied the FPVS oddball paradigm to investigate the effects of reading skills on the automatic neural response to sensitivity and familiarity contrast processing in second and third-graders. Until now, only one study has applied the FPVS paradigm to examine the differences between children with poor and typical reading skills (van de Walle de Ghelcke et al., 2020b). Reading deficiencies might impair automatic lexical differentiation, especially for fine lexical contrasts. The FPVS visual oddball design could highlight such differences between individuals with poor and typical reading skills.

In this study, we aim to better understand the range of sensitivity and familiarity during implicit visual processing in emergent reading children in 2nd to 3rd grade with poor versus typical reading skills. To measure the implicit degree of visual *sensitivity* to non-word oddballs, we inserted consonant string or false font oddballs in W bases (coarse contrast FFinW versus fine contrast CSinW; *Wbase*). In addition, we compared W, PW, and CS oddballs appearing in FF bases (WinFF, PWinFF, CSinFF), thus manipulating the coarse sensitivity contrast by the degree of familiarity with character strings. This combination of *FF-base* conditions with the target stimuli as oddballs thus provided us with a gradient of *familiarity* (W = familiar/lexical, PW = unfamiliar/non-lexical, but orthographically legal; CS = unfamiliar/non-lexical, orthographically illegal).

We expected discrimination responses at the oddball frequency with an occipitotemporal and left-lateralized distribution, as was observed in previous FPVS studies using print stimuli (Lochy et al., 2015, 2016). Furthermore, we predicted the oddball response to be graded for both oddball sensitivity (FFinW > CSinW) and oddball familiarity (WinFF > PWinFF > CSinFF) conditions because response amplitudes in previous studies were stronger when oddball-base differences were larger and expertise towards the stimuli was higher (Collins, Robinson, & Behrmann, 2018; Montani et al., 2019; van de Walle de Ghelcke, Rossion, Schiltz, & Lochy, 2020a). Further, we hypothesized the overall response magnitudes to correlate with children's reading scores (van de Walle de Ghelcke et al., 2020a) and to be more pronounced in children with typical than poor reading skills (group effect) (Lochy, Collette, Schelstraete, Rossion, & Schiltz, 2019). Finally, greater left-lateralized responses to orthographic deviants were expected in children with typical, but not poor reading skills, since previous studies have shown delayed or diminished lateralization of the OT in the latter group (Maurer, Brem, et al., 2005; Maurer et al., 2007; Pleisch et al., 2019). To summarize, our study aims to provide a more detailed insight into the implicit visual processing of different word-like stimuli with regard to print sensitivity and familiarity in early readers with typically and poorly developing reading skills.

2. Materials and methods

We report all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. For sample size determination, see: https://osf.io/85fv7/.

2.1. *Participants and group assignments*

In total, 96 native German-speaking children in 2nd to 3rd grade participated in a behavioral and an EEG session which were part of a longitudinal study on the efficacy of a phonics training for children with poor reading skills. One child did not complete the EEG task and the data of another three children had to be excluded due to slightly different experimental settings at the beginning of the study. The final sample of the cross-sectional study consisted of 92 native German-speaking children ($M = 8.80$ y, $SD = .63$ y).

All participants had nonverbal intelligence quotient (IQ) scores >80 (as estimated by the non-verbal intelligence index NIX subpart of the RIAS test; Hagmann-von Arx & Grob, 2014; Reynolds & Kamphaus, 2003), normal or corrected to normal visual acuity and reported no neurological or cognitive impairments, with the exception of dyscalculia (5 parentally-reported cases, 1 diagnosed by a specialist) and Attention Deficit (Hyperactivity) Disorder (AD(H)D, 9 cases with diagnosis, of which 4 under medication), which are known to often be comorbid with DYS (Boada, Willcutt, & Pennington, 2012; Germanò, Gagliano, & Curatolo, 2010; Kronenberger & Dunn, 2003). For the individuals taking medication, intake was discontinued at least 24 h before each experimental session. Parents gave written informed consent and children gave oral assent. Children received vouchers and presents in return for their participation. The project was approved by the local ethics committee of the Canton of Zurich (No. BASEC No. 2018-01261) and neighboring cantons in Switzerland. In- and exclusion criteria were established prior to data collection.

Based on a set of reading tests that examined reading comprehension (ELFE-II; Lenhard, Lenhard, & Schneider, 2018), word reading fluency (SLRT-II W; Moll & Landerl, 2014), and pseudoword decoding fluency (SLRT-II PW; Moll & Landerl, 2014), the children were grouped into participants with typical reading skills (TR: n = 35, 18 female, 16 in 2nd grade, 2 left-handed, 1 ambidextrous, $M = 8.69$ y, $SD = .58$ y, all reading measures ≥25th perc.), and poor reading skills (PR: n = 40, 20 female, 16 in 2nd grade, 5 left-handed, $M = 8.87$ y, $SD = .67$ y, at least 1 reading measure <16th perc. & mean of all

reading measures <25th perc.). 17 children (6 female, 7 in 2nd grade, 3 left-handed, $M = 8.86$ y, $SD = .65$ y) showed intermediate reading skills (IR) and were thus excluded from group analyses, but included for correlation analyses. Further demographic and behavioral information pertaining to the groups is presented in Table 1.

2.2. *Cognitive assessments*

Children each completed a battery of behavioral assessments. Table 1 contains a more detailed overview and description of the included tests. Percentile scores of the reading and decoding fluency measures (SLRT-II W, SLRT-II PW), and reading comprehension scores (ELFE II) were used to group participants as PR or TR (see Table 2). The behavioral sessions were held at the Department of Child and Adolescent Psychiatry and Psychotherapy (KJPP) or (during the COVID-19 pandemic) via online video sessions and took about 3 h.

2.3. *EEG task*

The present work presents EEG data recorded during the performance of an implicit oddball task denoted as Fast Periodic Visual Stimulation (FPVS). Participants were seated in a ventilated, electromagnetically shielded, and sound-attenuated EEG cabin and viewed the stimuli on a gray background on an LCD monitor with dimensions 60 × 35 cm^2, 2560 × 1440 screen resolution, and 144 Hz refresh rate (at a distance of 92 cm from the display). The font size of the stimuli was twice the size of the fixation cross, and the mean visual angle was 2.76° ($\sigma = .033$) horizontally and 1.32° ($\sigma = .020$) vertically.

The task was implicit and required participants to fixate on the centered cross and press a button in response to a rapid transient change in its color (blue to red, 194 msec duration) occurring at random intervals six times per block. The stimuli appearing behind the cross were not explicitly attended. Stimuli were presented using Neurobs Presentation® software (Version 20.1, www.neurobs.com).

The stimulation procedure was similar to previous FPVS EEG studies on print processing (Lochy et al., 2015, 2016). Each condition block commenced with a fixation cross presented for 2 sec. Base stimuli were presented in a continuous sequence at a rate of 6 Hz (one stimulus every 166.67 msec). Oddballs deviating from the base category were inserted at a rate of 1.2 Hz (i.e., every 5th item, 6 Hz/5). Fifty-five different

Table 1 – Descriptive statistics showing sample characteristics and behavioral test scores. Tests: Word reading fluency and pseudoword decoding: SLRT-II (Moll & Landerl, 2014); Reading comprehension: ELFE-II (Lenhard et al., 2018), Sentence reading fluency: SLS (2–9) (Wimmer & Mayringer, 2016); RAN: adapted from Mayer (2011); attention-deficit/hyperactivity: CBCL/4–18 subscore (Achenbach & Edelbrock, 1983; Döpfner, Berner, & Schmeck, 1994; Steinhausen & Winkler Metzke, 2011); familial risk for DYS: ARHQ (Lefly & Pennington, 2000); IQ: RIAS (Hagmann-von Arx & Grob, 2014; Reynolds & Kamphaus, 2003), Spelling: Schreib.on orthography test (May, 2008, 2010; Valtin & Hofmann, 2009), Vocabulary: PPVT-4 (Dunn & Dunn, 2007).

					PR vs. TR	
Test	TR [1] M (SD) [min,max]	IR M (SD) [min,max]	PR [1] M (SD) [min,max]	All [2] M (SD) [min,max]	Chi Square χ^2(df), *p*	t-test t(df), p
N	35	17	40	92		
School class (2nd:3rd)	16:19	7:10	16:24	39:53	$\chi^2(1)=0.249$, p=.618	
Sex ratio (female:male)	19:16	6:11	20:20	44:48	$\chi^2(1)=0.137$, p=.711	
Handedness (right:left:both)	32:2:1	14:3:0	35:5:0	81:10:1	$\chi^2(2)=2.096$, p=.351	
Age	8.67 (0.580) [7.49, 9.75]	8.83 (0.646) [7.47, 10.03]	8.85 (0.675) [7.29, 10.23]	8.78 (0.634) [7.29, 10.23]	$\chi^2(72)=70.982$, p=.512	t(73)=1.252, p=.214
Months since school start	30.85 (6.683) [16.53, 39.98]	27.90 (7.553) [17.22, 39.10]	28.99 (7.990) [16.49, 40.02]	29.49 (7.441) [16.49, 40.02]	$\chi^2(68)=68.304$, p=.467	t(73)=-1.083, *p*=.282
Reading						
Composite reading score: Average of word reading, pseudoword decoding, and comprehension (perc.) [3]	66.69 (19.812) [39.83, 99.00]	33.62 (11.390) [14.5, 55.5]	10.27 (7.376) [1.30, 24.53]	35.72 (30.101) [1, 99]	$\chi^2(72)=75.000$, p=.381	t(42.2)=-15.911, p<.001
Word reading fluency [4]	57.57 (21.960) [22, 101]	37.24 (12.691) [20, 71]	21.73 (8.400) [6, 38]	38.23 (22.418) [6, 101]	$\chi^2(46)=59.598$, p=.086	t(42.7)=-9.092, p<.001
Pseudoword decoding [4]	38.69 (12.043) [20, 72]	27.06 (6.814) [16, 44]	19.13 (5.412) [8, 30]	28.03 (12.39) [8, 72]	$\chi^2(35)=60.134$, p=.005	t(45.8)=-8.858, p<.001
Word reading fluency (perc.) [5]	65.70 (23.191) [25, 99]	31.65 (12.285) [18, 60.5]	6.26 (7.456) [1, 31.5]	33.57 (31.256) [1, 99]	$\chi^2(39)=72.991$, p<.001	t(40.1)=-14.520, p<.001
Pseudoword decoding (perc.) [5]	68.66 (21.178) [28.5, 99]	35.59 (18.891) [10, 74.5]	11.93 (12.127) [1, 40]	37. 88 (30.900) [1, 99]	$\chi^2(42)=68.304$, p=.006	t(52.5)=-13.970, p<.001
Reading comprehension (perc.) [5]	65.74 (26.179) [27.4, 99.4]	36.86 (25.219) [4.5, 84.1]	12.30 (9.68) [0.6, 38.2]	37.17 (31.525) [0.6, 99.4]	$\chi^2(34)=66.763$, p<.001	t(42.1)=-11.414, p<.001
Sentence reading fluency [6]	105.81 (15.604) [83, 138]	89.15 (8.297) [78, 108]	71.96 (7.936) [62, 90]	88.02 (19.116) [62, 128]	$\chi^2(48)=70.313$, p=.020	t(48.9)=-11.590, p<.001
RAN (Rapid automatized naming) Short animal names [4]	0.97 (0.213) [0.46, 1.50]	0.84 (0.131) [0.62, 1.16]	0.73 (0.181) [0.42, 1.19]	0.84 (0.214) [0.42, 1.50]	$\chi^2(68)=70.982$, p=.379	t(73)=-5.277, p<.001
RAN Long animal names [4]	0.97 (0.210) [0.46, 1.50]	0.84 (0.128) [0.59, 1.16]	0.72 (0.186) [0.42, 1.17]	0.84 (0.218) [0.42, 1.50]	$\chi^2(68)=68.973$, p=.444	t(73)=-5.554, p<.001
Attention-deficit/hyperactivity (t-values) [7]	52.41 (4.265) [50, 66] [8]	56.47 (7.392) [50, 73]	59.20 (9.918) [50, 88]	56.08 (8.507) [50, 88] [8]	$\chi^2(15)=21.037$, p=.136	t(72)=3.923, p<.001
Familial risk for DYS	0.34 (0.13) [0.09, 0.64] [9]	0.39 (0.13) [0.16, 0.61] [10]	0.41 (0.13) [0.17, 0.68] [11]	0.38 (0.13) [0.09, 0.68] [12]	$\chi^2(53)=52.142$, p=.508	t(71)=2.230, p=.029
IQ Nonverbal [6]	106.46 (7.983) [87, 120]	101.24 (8.197) [88, 114]	102.95 (6.008) [86, 113]	103.97 (7.438) [86, 120]	$\chi^2(31)=32.277$, p=.403	t(73)=-2.165, p=.034
IQ Verbal [6]	103.20 (11.383) [76, 121]	94.94 (16.649) [53, 117]	96.30 (9.107) [77, 112]	98.67 (12.069) [53, 121]	$\chi^2(40)=53.237$, p=.079	t(73)=-2.914, p=.005
Letter knowledge Names [4]	25.09 (1.269) [20, 26]	23.53 (3.744) [11, 26]	22.90 (4.137) [5, 26]	23.85 (3.378) [5, 26]	$\chi^2(11)=13.996$, p=.233	t(47.2)=-3.175, p=.003
Letter knowledge Phonemes [4]	24.69 (3.437) [6, 26]	24.88 (1.453) [20, 26]	24.68 (1.163) [22, 26]	24.72 (2.317) [6, 26]	$\chi^2(6)=9.715$, p=.137	t(73)=-0.019, p=.985
Spelling (perc.) [5]	55.40 (29.643) [8, 100]	33.00 (24.860) [5, 91]	14.55 (14.249) [1, 61]	33.50 (29.434) [1, 100]	$\chi^2(41)=54.710$, p=.074	t(47.4)=-7.436, p<.001
Vocabulary (perc.) [5]	62.25 (28.580) [18.4, 98.9] [14]	46.95 (31.031) [9.70, 98.90] [15]	50.48 (29.383) [8.1, 97.7] [13]	54.38 (29.707) [8.1, 98.9] [16]	$\chi^2(27)=23.029$, p=.683	t(69)=-1.705, p=.093

[1]Used for group comparison. [2]Used for correlation analyses. [3]Average of percentiles of reading comprehension and word and pseudoword reading fluency. [4]Raw scores: number of correct items (Letter-knowledge, total number of letters = 26), number of correct items named per second (RAN), and number of correct items read within 1 minute (SLRT-II). [5]perc. = percentile rank score, used for group assignment. [6]Intelligence quotient (IQ) or reading quotient (RQ) score. [7]Child Behavior Checklist. Normal range: t-values <65, subclinical range: t-values 65–69, clinical range: t-values >69. [8]1 missing case (TR N = 34, overall N = 74). [9]2 missing cases (N = 33). The familial risk level was low (ARHQ < .3) in 12 children (34.3 %), moderate (ARHQ range .3–.4) in 12 children (34.3 %), and high (ARHQ > .4) in 9 children (25.7 %). [10]Familial risk low in 4 children (23.5 %), moderate in 6 children (35.3 %) and high in 7 children (41.2 %). [11]Familial risk low in 10 children (25.0 %), moderate in 10 children (25.0 %) and high in 20 children (50 %). [12]2 missing cases (N = 90); low in 26 children (28.3 %), moderate in 28 children (30.4 %), and high in 36 children (39.1 %). [13]2 missing cases (N = 38). [14]2 missing cases (N = 33). [15]2 missing cases (N = 15). [16]6 missing cases (N = 86).

Table 2 – Linear Regression with reading test scores (raw scores) and baseline-subtracted amplitudes for the different conditions over LOT. Sorted top-to-bottom by highest R^2 value. +: survived Bonferroni multiple comparison corrected *p*-value of .0033 (15 tests, i.e., threshold of .05/15); trend: .1/15 = .0066.

Predictor	Predicted	R^2	*p*-value	Sample
Reading comprehension	LOT PWinFF	.141	**<.001**$^+$	87
(ELFE-II)	LOT FFinW	.144	**<.001**$^+$	88
	LOT WinFF	.095	.004	87
W reading fluency	LOT FFinW	.164	**<.001**$^+$	87
(SLRT-II)	LOT PWinFF	.087	.006	86
	LOT CSinFF	.057	.027	86
	LOT WinFF	.054	.031	86
PW reading fluency	LOT FFinW	.094	.004	88
(SLRT-II)	LOT CSinFF	.046	.045	87
	LOT PWinFF	.045	.049	87

stimuli were thereby repeated five times in a randomized order to achieve a total of 275 stimuli. Sinusoidal contrast modulation of stimuli enabled smooth transitions between the items. To avoid eye movements, a gradual fade-in (20 stimuli, 3.3 sec) and fade-out (15 stimuli, 2.5 sec) preceded and followed the full contrast stimulation sequence (40 sec, 240 stimuli, 48 oddballs, 240*.167 sec = 40 sec). The duration of one block was thus 240*.167 sec + 2 sec + 3.3 sec + 2.5 sec = 47.88 sec. Each condition block was presented twice, with short breaks between each condition block and a longer break between the two parts. If the experimenter noted movement during a condition block, the block was repeated at the end of the sequence of blocks. The procedure and conditions are illustrated in Fig. 1 and the Supplementary video.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.cortex.2023.12.010.

2.4. *Materials*

The task comprised four categories of stimuli: words (W), pseudowords (PW), consonant strings (CS), and false font strings (FF). Each stimulus was made up of four characters. Categories were combined pairwise, one serving as the "base", and one as the "oddball", to yield five different conditions: consonant strings as oddballs embedded in word bases (CS in W), false font in words (FF in W), words in false font (W in FF), consonant strings in false font (CS in FF), and pseudowords in false font (PW in FF). Fifty-five concrete, one-syllable German words were selected from the ChildLex database (age range 6–8) (Schroeder, Würzner, Heister, Geyken & Kliegl, 2015) and 55 pseudowords were generated using WordGen (Duyck, Desmet, Verbeke, & Brysbaert, 2004), matching them to the words in bigram frequency (t_{108} = .06, p = .956) and orthographic neighborhood size (t_{108} = .25, p = .801). Alternating between words and pseudowords, vowels were systematically replaced with consonants (i.e., always the same consonant inserted for the same vowel) to obtain consonant strings matched to the other categories. The false font was constructed based on the real font in the experiment (Swiss school font "Steinschrift") using FontCreator 11.5 (High-Logic, Utrecht, Netherlands). For each letter, symbol elements were shuffled and re-oriented while maintaining their size, number, and complexity. A balanced number of items from our pool of words, pseudowords, and consonant strings were then written in the false font script to build the false font strings.

2.5. *EEG data acquisition and preprocessing*

EEG data were recorded at a sampling rate of 1000 Hz using a high-density 128-channel EEG system (Net Amps 400, EGI HydroCelGeodesic Sensor Net). A DC filter and anti-aliasing

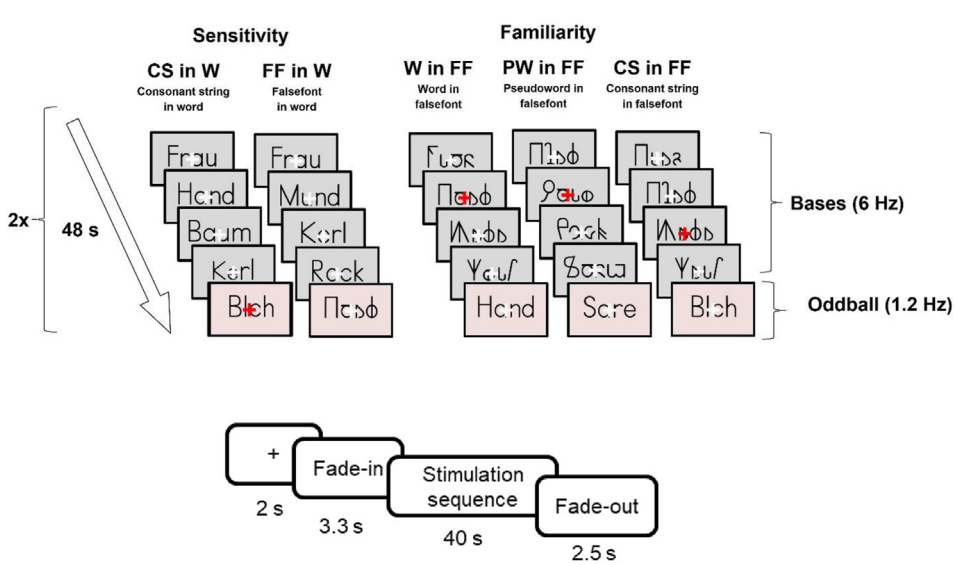

Fig. 1 – Experimental Paradigm. Above: Example base and oddball stimuli of the different conditions (grouped by model) are shown. Randomized order of stimuli presented for about 48 sec non-stop. The task was divided into two equal parts with a break in between. Below: Representation of the timeline of one block.

filter were applied and electrode Cz was used as the recording reference, the electrode just posterior to Cz as the ground (COM). Electrode impedances were kept below 50 kΩ.

Data were preprocessed in BrainVisionAnalyzer 2.1 (BrainProducts GmbH, Munich, Germany). First, data were segmented to exclude blocks that had to be interrupted due to movement and breaks in between sequences. The separate EEG blocks of the same subject from the different conditions were concatenated. A .1 Hz high-pass filter and a 50 Hz Notch filter were then applied. Data were visually inspected and manually marked for bad intervals (to exclude them from the ICA decomposition). Noisy- or artifact-ridden channels were then topographically interpolated (number of channels interpolated per subject: $M = 4.15$, $SD = 3.33$, range = 0–12). Due to the purported high signal-to-noise ratio of the FPVS analysis method (Lochy et al., 2015, 2016), we included most of the data. However, sequences that contained roughly more than 25 % strong artifacts (greater than 150 μV) were rejected. A repeated measures ANOVA showed no significant differences in the number of blocks for the different conditions ($F_{5.46,\ 398.21} = .853$, $p = .521$), the two groups ($F_{1,\ 73} = 2.64$, $p = .108$), or an interaction between the two ($F_{5.46,\ 398.21} = .625$, $p = .695$). Data were then downsampled to 512 Hz and IC components associated with ocular artifacts were removed by performing an independent component analysis (ICA; number of components removed: $M = 3.93$, $SD = 2.09$). We then re-referenced to the common average. Finally, a low-pass zero-phase-shift Butterworth filter (100 Hz, order 8) was applied to remove residual artifacts. The 40 sec stimulation sequence without fade-in and fade-out was extracted from the continuous EEG by segmenting from 3333 msec to 43334 msec after block onset. The different blocks' segments were averaged per condition and individual in the time domain to diminish any activity not phase-locked to the stimuli.

2.6. *Frequency analysis*

A Fast-Fourier Transform (FFT) was applied to convert the data into the frequency domain. Amplitude spectra were extracted (per single subject, group, and condition) for each electrode and exported for further analyses using R (RCoreTeam, 2021) in-house scripts. We selected literature-based clusters of electrodes over the left (LOT: E050, E057, E058, E059, E063, E064, E065, E066, E068, E069, E070, E073, E074) and right occipitotemporal cortex (ROT: E082, E083, E084, E088, E089, E090, E091, E094, E095, E096, E099, E100, E101: c.f. Supp. Fig. 1; Pleisch et al., 2019). Z-scores (amplitude at each frequency minus the average of 20 surrounding bins divided by the standard deviation of the 20 surrounding bins) were computed on the grand average of the spectra per group, condition, and electrode cluster. This was done to assess the response significance at the oddball frequency and each harmonic (multiples of 1.2 Hz, i.e., of the oddball frequency) and thereby determine the number of harmonics to include in the statistical models. Z-scores of 1.96 and above were considered significant. Based on the highest number of consecutive harmonics to exceed this threshold in any group, electrode cluster, or condition, we selected an identical number of harmonics across all groups (including the intermediate group), electrode clusters (averaged before computing Z-scores), and conditions included per statistical model (as described in section 'Statistical Analysis'). In total, we included 5 harmonics (H1 to H5, i.e., multiples of 1.2 Hz up to 7.2 Hz, excluding base frequency) for model "familiarity" and 3 harmonics (H1 to H3, i.e., multiples of 1.2 Hz up to 3.6 Hz) for model "sensitivity". For the quantification of the periodic oddball response spread out across harmonics, we then summed the baseline-subtracted amplitudes (i.e., the average voltage amplitude of the 20 surrounding bins subtracted out) at the oddball- and harmonic frequency bins (see e.g. Retter & Rossion, 2016 for validation of procedure).

2.7. *Statistical analysis*

Two linear mixed models (LMM) with the sum of baseline-subtracted amplitudes as the dependent variable were defined and fitted in SPSS® (IBM-Corporation, 2020): i) "sensitivity" and ii) "familiarity". Both models had a random subject intercept and the fixed factors group [poor/typical], hemisphere [LOT, ROT], condition [i) sensitivity: FF/CS in W as base; ii) familiarity: W/PW/CS embedded in FF as base]. Nonverbal IQ and child behavior checklist (CBCL; Achenbach & Edelbrock, 1983; Döpfner et al., 1994; Steinhausen & Winkler Metzke, 2011) attention deficit/hyperactivity subscore t-values were included as covariates due to differences between the groups (see Table 1) and due to high comorbidity of reading- and attentional difficulties (Boada et al., 2012; Kronenberger & Dunn, 2003). Post-hoc pairwise comparisons were corrected using Bonferroni. We report significant values ($p \leq .05$) and statistical trends ($p \leq .1$) but restrict our discussion mainly to significant values. To reduce bias by outliers and extreme values, we iteratively removed normalized (z-score) residuals that exceeded a threshold of ±3 (see e.g. Fraga-González et al., 2021). In total, 6 data points out of 296 (2.02 % of the data) were removed in model "sensitivity" and 11 out of 444 data points (2.48 % of the data) were removed in model "familiarity".

Linear regression was performed using R (R Core Team, 2021) to analyze the association between neural (baseline-subtracted amplitudes per condition) and behavioral measures of interest (word- and pseudoword reading fluency and text reading comprehension) over LOT (i.e., 15 contrasts were tested). These tests were performed after the exclusion of outliers (1.5 IQR criterion) to exclude spurious findings (see the corresponding sample in the table).

Lastly, plots of scalp topographies of the sum of baseline-subtracted amplitudes at each oddball harmonic (including all oddball harmonics up to the pre-determined number except the base, see description above), and t-maps between conditions and groups were created in EEGlab (Delorme & Makeig, 2004), a Matlab-based toolbox (R2020b, MathWorks, Natick, MA). For the t-maps, we computed electrode-wise pairwise comparisons of the baseline-subtracted oddball amplitude sums: To measure conditions against each other, we used paired two-sided *t*-tests, and to compare the PR and TR groups, we used independent two-sided *t*-tests. Further, we applied the R-based DuckDB (Raasveldt & Mühleisen, 2019) to compute the subject-wise difference between condition-pairs' mean sum of oddball harmonic amplitudes, which were then compared between the groups using independent two-sided electrode-wise *t*-tests.

3. Results

3.1. Oddball discrimination responses

3.1.1. Oddball response amplitudes by reading level

3.1.1.1. Presence of significant z-scores of responses at the oddball frequency. To test for the presence of discrimination responses in the different conditions, hemispheres, and groups, z-scores at the oddball frequency and its harmonics were examined. Discrimination responses (significant z-scores at target oddball and harmonic frequencies) were detected in both models in all conditions in at least one hemisphere and one group except for CSinW (WinFF: H1–H4 in PR, H1–H5 in IR and TR; PWinFF: H1–H3 in PR, H1–H4 in IR and TR; CSinFF: 0 in PR and IR, H1–H4 in TR; FFinW: H1–H3 for all groups). A maximum of three consecutive harmonics for model i) "sensitivity" (1.2–3.6 Hz, excluding the base rate at 6 Hz) and five consecutive harmonics (from 1.2 to 7.2 Hz, excluding the base rate at 6 Hz) for model ii) "familiarity" were thus found to be significant. More detailed information on the number of consecutively significant harmonics per group, electrode cluster, and condition can be found in Supp. Tables 1 and 2. Additionally, the supplementary information includes an exploratory inspection of the spread of amplitudes across the harmonics (i.e., individually instead of analyzing the sum of consecutively significant harmonics; Supp. Fig. 2). Frequency spectra and topographical scalp maps of the sum of amplitudes at oddball harmonics are shown in Fig. 2.

3.1.1.2. Topographic evaluation of response amplitudes at the oddball frequency. To investigate our hypothesis regarding the occipitotemporal and left-lateralized distribution of the oddball discrimination responses, as well as the predicted greater left-lateralization in TR than PR, we computed topographic maps and t-maps (Fig. 2). In TR, the sum of oddball harmonics shows a clear left-lateralized occipitotemporal topographical profile and responses are stronger for oddballs that differ strongly from the base (FFinW > CSinW; sensitivity model) and for more familiar oddballs (W > PW > CS in FF; familiarity model). These effects appear reduced or inconsistent (e.g., right-lateralization for FFinW) in PR.

T-maps for pairwise comparison of the sensitivity conditions show significantly greater activity for FFinW than CSinW in bilateral but right-lateralized occipitotemporal areas in PR, and bilateral left-lateralized occipitotemporal and central regions in TR. A comparison of the groups showed greater activity in left occipitotemporal electrodes in TR than in PR. In CSinW, a right-hemispheric occipitotemporal cluster of electrodes was also observed to show a significant group difference (TR > PR).

T-maps for the familiarity conditions revealed significant left-hemispheric occipitotemporal differences for both WinFF – CSinFF and PWinFF – CSinFF in TR. On the other hand, PR showed bilateral, less focalized posterior differences. In the group comparison per condition, TR showed greater responses than PR over a left posterior, a central, and a right-frontotemporal region in WinFF. In CSinFF, the t-map suggests higher response amplitudes across the (bilateral) posterior scalp for TR than PR. PWinFF showed no notable differences between the groups. PR appear to have displayed a greater difference in response amplitudes between the PWinFF and CSinFF conditions than TR over a right-hemispheric occipital area. For the comparison of WinFF with the other two conditions, TR showed greater amplitude differences than PR over central (WinFF-PWinFF) and over central and right fronto-temporal areas (WinFF-CSinFF).

3.1.1.3. Linear mixed model analyses. Two linear mixed model (LMM) analyses i) "sensitivity" and ii) "familiarity" were performed on the summed baseline-subtracted amplitudes of the specified number of significant harmonics (see Section 2.6. Statistical analysis for description). We used these models to test differences in the level of sensitivity (FFinW > CSinW) and familiarity with (WinFF > PWinFF > CSinFF) the oddball stimulus, depending on the hemisphere and reading group. In the "sensitivity" model (Fig. 3), there was a significant main effect of *condition* ($F_{1,\ 211.96} = 158.53$, $p < .001$), indicating stronger oddball amplitudes for FFinW than CSinW. Furthermore, a *hemisphere* effect ($F_{1,\ 212.03} = 6.27$, $p = .013$) revealed increased responses over LOT compared with ROT. In addition, there was a *group* main effect ($F_{1,\ 69.72} = 4.26$, $p = .043$), generally showing greater oddball response amplitudes for TR as compared with PR. Main effects were qualified by a *condition-hemisphere-group* interaction ($F_{1,\ 213.73} = 5.07$, $p = .025$). Amplitudes in response to FFinW were stronger over LOT than ROT in TR, but not PR ($t_{213.77} = 3.19$, $p_{Bonferroni} = .002$). Correspondingly, oddball responses to FFinW were stronger over LOT for TR than PR ($t_{258.76} = 3.58$, $p_{Bonferroni} < .001$). Lastly, there was a trend for a main effect of the CBCL attention-deficit/hyperactivity covariate ($F_{1,\ 68.65} = 3.63$, $p = .061$). No further trends or significant effects were found.

In the "familiarity" model (Fig. 4), we found main effects of *condition* ($F_{2,\ 347.68} = 7.09$, $p < .001$), *hemisphere* ($F_{1,\ 346.86} = 31.89$, $p < .001$), and a trend for *group* ($F_{1,\ 66.85} = 3.19$, $p = .079$). Overall, post-hoc pairwise comparisons of conditions showed oddball discrimination amplitudes to be significantly stronger for both WinFF and PWinFF than CSinFF ($t_{348.63} = 3.57$, $p_{Bonferroni} < .001$ and $t_{346.74} = 2.77$, $p_{Bonferroni} = .017$, respectively). The main effect of hemisphere pointed to stronger oddball amplitudes over LOT than ROT. Finally, we found a trend for a three-way interaction of *condition-hemisphere-group* ($F_{2,\ 346.85} = 2.78$, $p = .063$). Post-hoc contrasts revealed that familiarity effects were only present over LOT for TR (PWinFF > CSinFF: $t_{346.11} = 2.52$, $p_{Bonferroni} = .037$), and only over ROT for PR (PWinFF > CSinFF: $t_{346.11} = 2.56$, $p_{Bonferroni} = .033$; CSinFF > WinFF: $t_{347.08} = 2.61$, $p_{Bonferroni} = .030$): Further hemispheric differences included increased responses to CSinFF over LOT compared with ROT ($t_{346.61} = 2.21$, $p_{Bonferroni} = .028$), for PR and a trend for the same effect in WinFF ($t_{346.11} = 1.76$, $p_{Bonferroni} = .079$). Further non-significant values or trends were found for TR versus PR with regards to CSinFF amplitudes over ROT ($t_{228.35} = 1.95$, $p_{Bonferroni} = .052$), but not LOT ($t_{227.99} = 1.59$, $p_{Bonferroni} = .112$). Both WinFF ($t_{347.93} = 2.05$, $p_{Bonferroni} < .042$) and PWinFF elicited enhanced amplitudes over LOT than over ROT in TR only ($t_{346.11} = 4.99$, $p_{Bonferroni} < .001$). PWinFF response

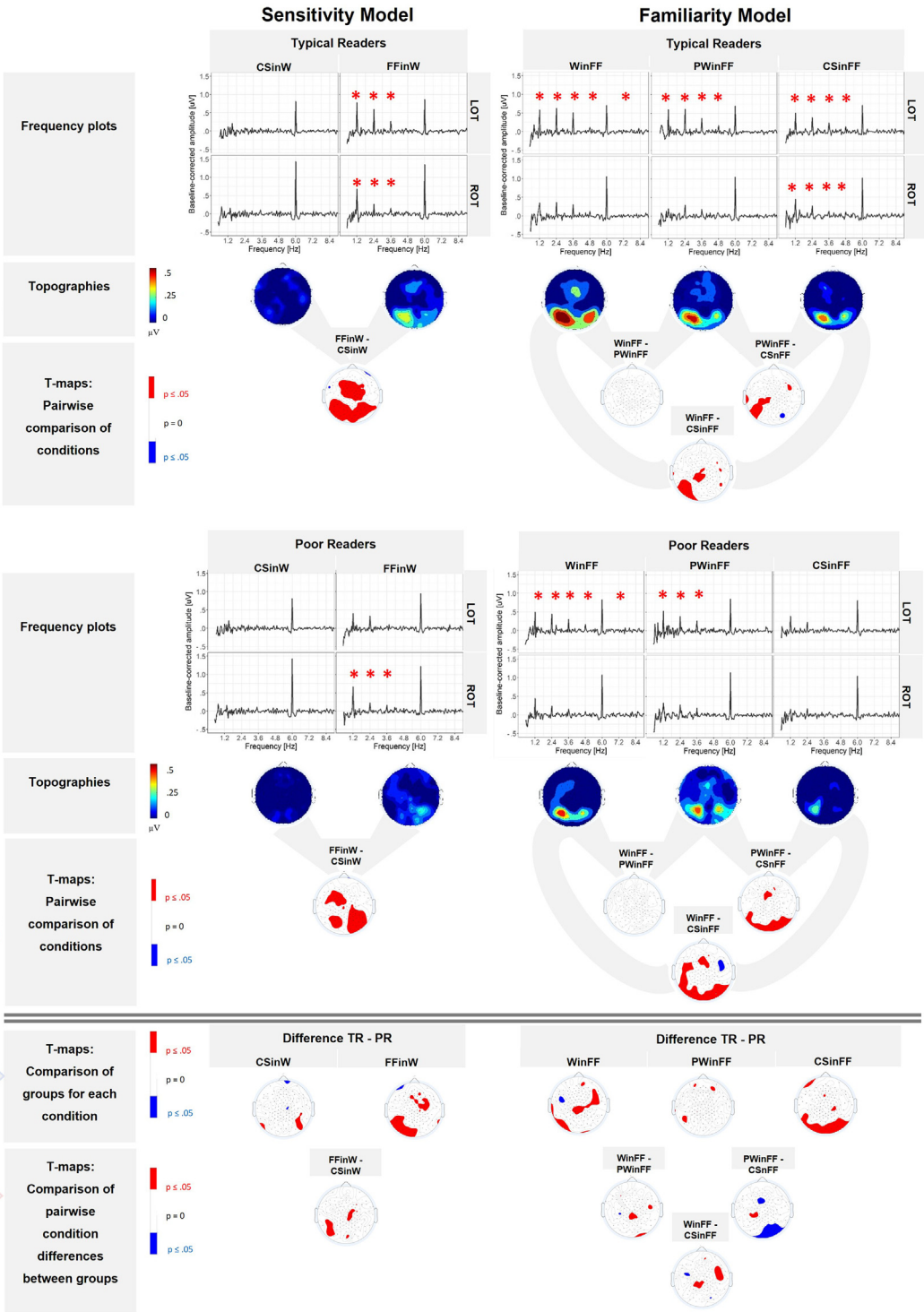

Fig. 2 – Left panel (Sensitivity model): Baseline-subtracted amplitude frequency spectra of the "sensitivity" conditions for typical and poor readers in left (LOT) and right (ROT) occipitotemporal electrode clusters. The figure shows frequency spectra and topographies of the sum of baseline subtracted amplitudes across the relevant harmonics (i.e., average amplitude over 3 harmonics) for TR (above) and PR (below). Oddball harmonics that reached significance according to Z-scores >1.96 are marked by a red asterisk in the frequency spectra. Below the topographies, t-maps display the group-wise comparison of topographical scalp maps across conditions (t-tests). Panel B shows the condition-wise comparison of groups (row 1, TR-PR), and the comparison of pairwise condition-differences across the groups ("double-difference", rows 2–3). For the t-maps, red and blue denote significantly greater and lower sums of harmonic amplitudes (respectively) in TR than PR. Activity in OT regions was observed only for FFinW and showed diverging lateralization in the groups. Right panel (Familiarity model): Same as left panel for "familiarity" conditions. Responses are stronger in the left hemisphere, in TR, and for more familiar oddball stimuli.

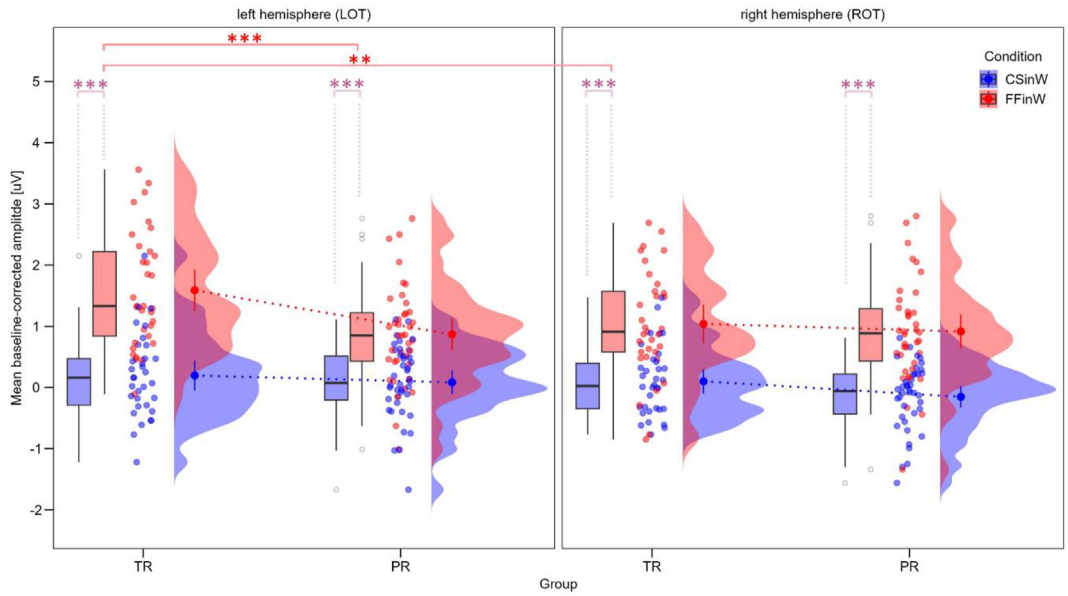

Fig. 3 – "Sensitivity" Linear Mixed Model Results. Mean normalized amplitudes for the different groups, conditions, and hemispheres are shown. A significant three-way interaction between these factors was found. Stars represent significant differences as determined by linear mixed model post-hoc pairwise comparisons: $p \leq .001$*, $p \leq .01$**, $p \leq .05$*. CS = consonant strings, W = words, FF = false fonts; TR = children with typical reading skills, PR = children with poor reading skills, LOT = left occipitotemporal electrode cluster, ROT = right occipitotemporal electrode cluster.**

magnitudes over LOT ($t_{230.75} = 2.49$, $p_{Bonferroni} = .014$), but not ROT ($t_{225.61} = .63$, $p_{Bonferroni} = .532$) were also increased in TR compared to PR. No further significant effects or trends were found.

Models including participants with intermediate reading skills are shown in Supp. Fig. 3 (sensitivity) and Supp. Fig. 4 (familiarity) and largely support the results of the main analyses.

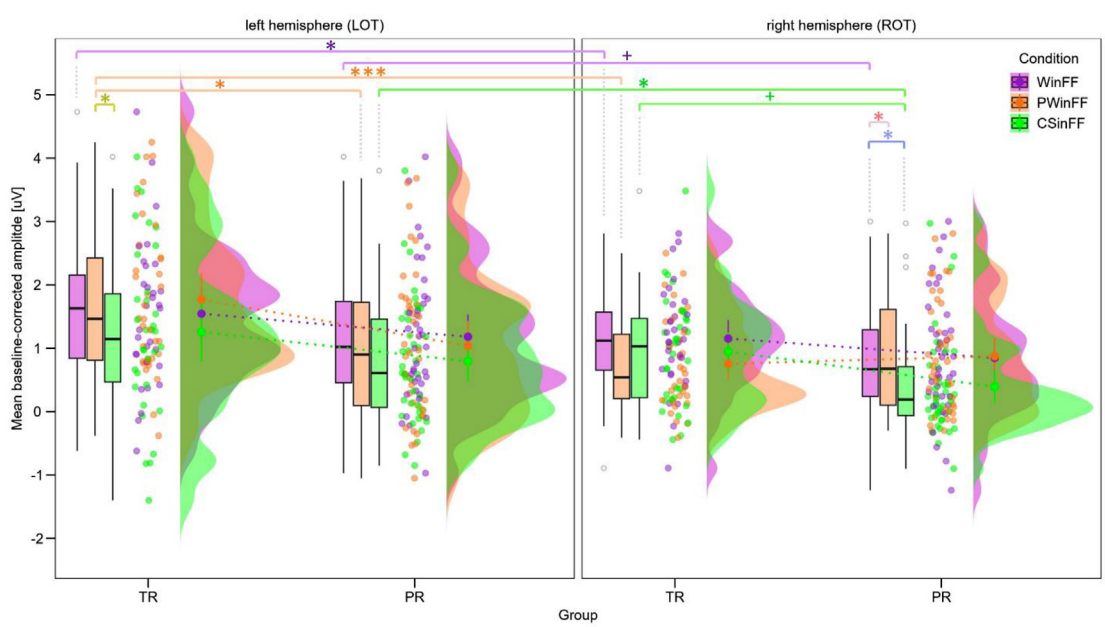

Fig. 4 – "Familiarity" model. Mean normalized amplitudes for the different groups, conditions, and hemispheres are shown. A trend for a three-way interaction of these factors was found. Asterisks represent differences as determined by linear mixed model post-hoc pairwise comparisons of this interaction: $p < .001$*, $p < .01$**, $p < .05$*, $p < .1$ +. CS = consonant strings, PW = pseudowords, W = words, FF = false fonts. TR = children with typical reading skills, PR = children with poor reading skills, LOT = left occipitotemporal electrode cluster, ROT = right occipitotemporal electrode cluster.**

3.1.2. *Brain–behavior associations*

We computed brain-behavior correlations to clarify whether the response magnitudes of oddball responses are related to children's reading skills. Here, we found a significant association between word reading fluency and FFinW oddball responses and between reading comprehension with FFinW and PWinFF oddball responses (shown in more detail in Table 2 and Fig. 5; only tested for LOT, not ROT, see Methods). These associations indicate that oddball response magnitudes over LOT increase with reading skills. Further trends for brain-behavior associations that did not survive multiple comparison corrections can be found in Table 2.

4. Discussion

We applied an oddball paradigm to examine potential differences between children with typical and poor reading skills in their ability to implicitly discriminate between orthographic lexical, orthographic non-lexical, and non-orthographic stimuli in a fast-paced visual presentation. First, we used orthographic versus non-orthographic (CS, FF) oddballs in W bases to test fine (CSinW) versus coarse (FFinW) sensitivity, i.e., the presence and level of neural discrimination responses to print in children. In addition, we were interested in the strength of responses in TR versus PR to oddball items along a gradient of orthographic familiarity and legality (oddballs W > PW > CS) embedded in a sequence of unfamiliar FF base items. Our results show consistent oddball effects for coarse tuning to print (coarse sensitivity; FFinW) in children in 2nd–3rd grade and indicate that the strength and lateralization of the coarse tuning responses depend on reading skills. Importantly, linear regression models indicated that the strength of the coarse sensitivity over LOT is positively associated with the reading skills of the children. The effects of the level of familiarity with word forms were less pronounced. Oddball effects distinguished between orthographically legal and illegal items (W/PW *vs* CS) but not yet between lexical and non-lexical (W *vs* PW) word forms. Altogether, effects of familiarity tended to differ between groups and hemispheres, with TR showing familiarity effects mainly over the left hemisphere, while such effects were observed over the right hemisphere in PR. These main findings will be discussed in more detail in the next sections.

4.1. *Oddball discrimination conditions reveal coarse but no fine sensitivity to print*

In agreement with previous reports (Lochy et al., 2016), we found oddball responses to the familiarity conditions in all groups. This suggests that orthographic stimuli triggered brain activity that was distinct from the state evoked by false fonts. The participants were thus able to automatically discriminate between letter-containing items and a false script (WinFF, PWinFF, CSinFF) and therefore show coarse sensitivity to print, as we expected for children of this age

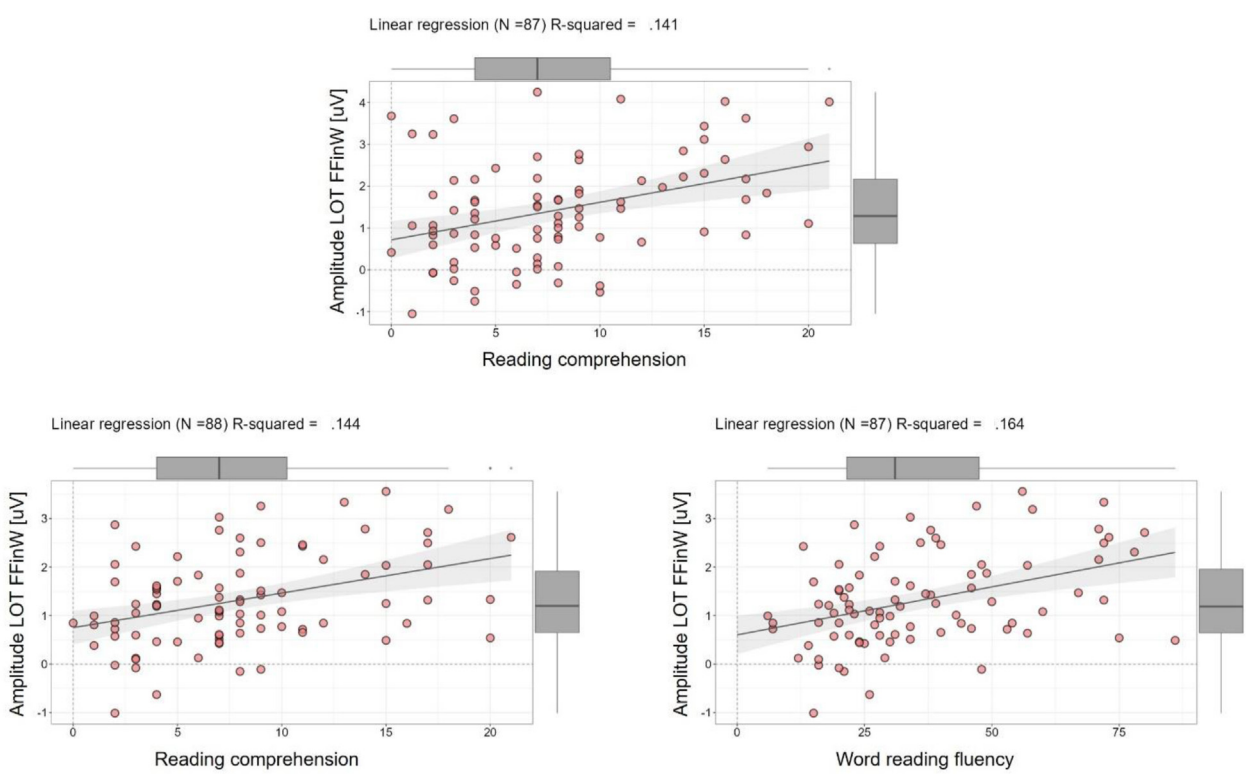

Fig. 5 – Brain-behavior association plots of significant linear regression outcomes between reading test scores (raw scores) and baseline-subtracted mean amplitudes for the different conditions in the left hemispheric electrode cluster (LOT). The shaded area around the fitted line shows the 95 % confidence interval. Boxplots to the side of both axes visualize the distribution of the behavioral and neural data values.

(Lochy et al., 2016; Maurer et al., 2006; van de Walle de Ghelcke et al., 2020a). Similarly, significant oddball responses to FFinW, but not to CSinW conditions suggest that coarse print sensitivity has already emerged in all participants, while fine discrimination of words from other letter strings (i.e., familiarity) is not yet detectable with a fast implicit processing task.

Previous studies have reported conflicting findings regarding fine discrimination in young children. In FPVS literature, for example, no PW versus W distinction was found in children (Lochy et al., 2016; van de Walle de Ghelcke et al., 2020a, 2020b; children in these studies were 5–7 years old and French-speaking). Although PW are orthographically legal while CS are not, both PW and CS are orthographic stimuli, and thus both difficult to discriminate from words for early readers. In support of this, a study described 7–14-year-old children's VWFA print "sensitivity" as full-fledged, yet the "specificity" towards letters and words as immature (Centanni et al., 2017). It thus appears that the fundamental skill set for reading is obtained early on in learning (Aghababian & Nazir, 2000, p. 123), but that it takes more time to specialize in word processing (Brem et al., 2006; Coch & Meade, 2016, p. 115) and to become quicker at gathering information from print (Aghababian & Nazir, 2000, p. 123). However, a very recent study found evidence for lexical and sublexical processing in children at early reading stages (kindergarten to second grade) (Wang et al., 2022). The study used an adapted SSVEP task design (alternating between two stimulus types and doing so at a slower pace than previous studies) and reliable component analysis. They compared coarse print tuning, lexical processing, and sublexical orthographic processing using W versus FF, W versus PW, and PW versus nonword (unpronounceable letter combinations with lower orthographic neighborhood and bigram frequencies than PW) contrasts. The authors interpret these methodical modifications to the FPVS as the defining features enabling higher signal detection. In other words, it might be that a lexical discrimination effect in children emerges only at slower presentation rates and more sensitive analysis methods. Further studies are needed to replicate these results and provide more clarity as to the discrepancies between studies.

4.2. *Strong coarse sensitivity and emerging familiarity discrimination in children with typical reading skills over the left hemisphere*

In our sensitivity model, we found significantly greater oddball responses in TR than in PR, and this group difference was especially pronounced over the left hemisphere. Diminished left occipitotemporal coarse print sensitivity in PR is in line with previous studies using classical ERP designs (Eberhard-Moscicka et al., 2015; Maurer et al., 2007; Pleisch et al., 2019) or FPVS (van de Walle de Ghelcke et al., 2020b), although one previous report did not find differences between reading groups for coarse, but only for lexical and sublexical processing (Wang et al., 2022). The familiarity model supported the results of the sensitivity model in that the degree of discrimination along a gradient of familiar versus unfamiliar and orthographically legal versus illegal character strings tended to differ according to reading skills and hemisphere. Previous literature has described the preferential activity of vOT to familiar print to become predominantly left-lateralized with reading acquisition (Brem et al., 2006; McCandliss et al., 2003; Rossion, Joyce, Cottrell, & Tarr, 2003; Seghier & Price, 2011; Zhao et al., 2012). In our study, we found electrodes over LOT to generally activate more strongly to the oddballs than those over ROT.

In TR, the discrimination response amplitudes to orthographically legal word forms (WinFF and PWinFF) were significantly higher than those to illegal ones (CSinFF) over LOT in the differential t-maps for the contrasts between WinFF-CSinFF and PWinFF-CSinFF, respectively. There was, however, no significant difference for the WinFF-PWinFF t-map contrast. This indicates that TR already differentiate between legal (W, PW) and illegal (CS) orthographic oddballs presented amidst FF base, but not yet between familiar and unfamiliar word form oddballs (PW and W) amidst FF base over the left-hemispheric vOT (Panda et al., 2022). PR also show significant differences in the t-map comparison of conditions, but the significant electrode locations were more bilateral, covering large parts of the ventral occipital and posterior temporal sites. Notably, the group-hemisphere-condition three-way interaction over LOT and ROT did not reach significance in the "familiarity" LMM. This may be explained by the selection of the a priori defined electrode clusters covering large parts of the occipito-temporal and inferior parietal cortex. Previous studies have reported greater activation of the vOT/VWFA, with a left hemisphere bias, the more frequent or familiar the letter combinations of word-fragments were, or the more word-like the stimuli (Vinckier et al., 2007). Therefore, our results suggest that W and PW are processed as more familiar and as more distinguishable from FF than CS by TR, while in PR this lateralization appears less clear.

The results are thus largely in line with our expectations based on previous studies. Although to our knowledge, there is no previous FPVS study comparing W and CS, previous studies have tested the fine contrast of W and PW. For instance, W embedded in PW (WinPW) did not yield a significant discrimination response (Lochy et al., 2016; van de Walle de Ghelcke et al., 2020a) and WinFF versus PWinFF did not differ significantly in children (Lochy et al., 2016; van de Walle de Ghelcke et al., 2020a, 2020b). In adults, WinPW differences indicating lexical differentiation of orthographically legal strings could previously be observed in FPVS paradigms (Lochy et al., 2015), albeit not consistently (Barnes, Petit, Badcock, Whyte, & Woolgar, 2021). It is important to emphasize that the children in the aforementioned studies were pre-schoolers or first- and at most second-graders in the first trimester, thus beginning readers. In more classical visual ERP paradigms, evidence on fine-tuning in young children remains mixed: some studies found no significant N1 ERP difference between W and CS (Posner & McCandliss, 1999) or PW and W (Eberhard-Moscicka et al., 2015) in 4- and 7-year-old children, or even older children (9–13 years (Araújo et al., 2012); 8–12 yrs (Kast, Elmer, Jancke, & Meyer, 2010). However, children with high reading skills may show such fine-tuning between orthographically legal and illegal strings already at an early age (7 yrs) (Zhao et al., 2014). The children in our study were at a more advanced reading stage (2nd–3rd grade) and were learning to read an orthographically rather

transparent alphabetic language (German). Our finding of an emerging fine sensitivity for orthographically legal versus illegal strings (PWinFF versus CSinFF) in our typically reading children thus supports the rapid and critical changes occurring during the early school years, paralleling the development of sight word reading (Maurer et al., 2011; Wang et al., 2022).

4.3. *Altered hemispheric patterns in PR may indicate developmental delay or compensatory strategies*

Although PR showed significantly stronger discrimination amplitudes to FFinW than CSinW both in the left and right hemisphere, the responses were weaker than in TR and showed no significant lateralization. Topographic plots even indicate a more right-hemispheric occipito-temporal activation for FFinW in PR.

For the familiarity model, the t-map comparison of pairwise condition differences between groups also showed an increased difference between PWinFF and CSinFF over the right occipitotemporal scalp in PR compared to TR. However, in the linear mixed models, we did not find a significant difference in the processing of PWinFF and CSinFF, but only found trend-level evidence for greater activity to W and PW than to CS oddballs in FF over the right hemisphere of PR.

The reduced and more right-lateralized activation for and differentiation between oddballs could either reflect a delayed development (Maurer et al., 2011) or beginning compensational processes in children with poor reading skills. Indeed, different developmental trajectories of print processing in PR have previously been referred to in literature (Maurer et al., 2011). The lateralization, indicative of print specialization, develops only with intensive training and over time (Eberhard-Moscicka et al., 2015; Maurer, Brem, et al., 2005; van Setten, Maurits, & Maassen, 2019). Several studies report discrepant laterality findings in children. For example, Kast et al. (2010) report missing lateralization in 8- to 12-year-old readers and attribute it to incomplete maturation or reading expertise. Similarly, Spironelli and Angrilli (2009) found greater visual N1 right-lateralization in 10-year-olds. Before reading instruction at school, visual familiarity with print and higher letter knowledge was reflected in a right-lateralized N170 (Maurer, Brem, et al., 2005; Maurer et al., 2006). Similarly, in an artificial script training study with adults, emerging N170 responses to the trained script were more pronounced over the right rather than the left hemisphere after a 20-min training phase (Maurer et al., 2010). Thus the right hemisphere seems more involved in the beginning stages of reading acquisition before the typical left hemispheric dominance develops (Maurer et al., 2010; Seghier & Price, 2011). Further longitudinal research will be necessary to clarify whether such an activation pattern in the ROT might precede the fine-scaling in the LOT, indicative of a developmental delay in PR.

Another interpretation could be compensatory activity specific to PR. In fMRI studies (Borghesani et al., 2021; Centanni et al., 2019), researchers found a missing word tuning effect (W > FF) and a hypoactivation to letters and FF in poor compared to TR in the left hemisphere (Ozernov-Palchik & Gaab, 2016). Furthermore, greater functional connectivity among right-hemispheric brain areas has been observed for groups with more severe reading problems (Panda et al., 2022). Right hemispheric activation in PR has been reported as a mechanism to compensate for the left-hemispheric hypoactivation (Démonet et al., 2004; Pugh et al., 2000; Shaywitz et al., 1998; Turker, 2018; Waldie et al., 2013). Compensatory refinement of the ROT may be driven by more pictorial, rote-learned representations of stimuli, given the evidence for greater involvement of the right vOT in deep orthographies and the visual appraisal of familiar objects, drawings, and symbols that are not linked to phonology (Lochy et al., 2016; Maurer, Brandeis, et al., 2005; Mei et al., 2013; van de Walle de Ghelcke et al., 2020a).

In summary, the discrepant lateralization patterns between the groups are likely to arise from delayed reading development or compensatory strategies in PR. However, further data sampling time points would be required to attribute our findings to persistent developmental differences or delayed development.

4.4. *Limitations and outlook*

There are several aspects of the current paradigm that may have impacted our results. One of them is the stimulation frequency. A recent report explored two frequency variations (2 Hz oddball, 10 Hz base *vs* 3 Hz oddball, 6 Hz base) for WinFF contrasts (Wang et al., 2021, 2022). The two variations elicited a similar pattern of responses, although amplitudes were larger for the slower presentation rates. Further studies should investigate the impact of such stimulation differences in more detail and in different age groups.

Further, the paradigm we used was implicit. The attention was therefore not specifically directed to the stimuli, which could affect the engagement of the reading system. Specifically, higher-level reading processes might be engaged to a greater degree when there is an overt reading-related task requirement in contrast to an implicit task (Maurer et al., 2006; Okumura, Kasai, & Murohashi, 2015; Wang et al., 2021; Yoncheva et al., 2010). Future studies should thus compare implicit and explicit approaches to study this effect of task design.

It is important to note that the present analyses are complex, including three fixed factors and two covariates. A design with many variables could potentially limit our power, despite the large sample of children. However, these variables were important to test our hypotheses relating to group, condition, and lateralization differences and to account for possible confounding effects. We included nonverbal IQ and the attention-deficit/hyperactivity subscore as covariates to account for potential differences related to IQ and attention. This consideration is further justified by the high comorbidity of reading impairments and ADHD (Boada et al., 2012). In the supplementary material (section S5), we also provide an overview of the results of the same models without the covariates. Future studies will be critical to corroborate the present results and conclusions.

An additional factor warranting consideration is statistical regularity. A recent study by De Rosa et al. (2022) noted that participants exhibited an oddball discrimination

response not only to stimuli differing in category but also to those differing merely in frequency of occurrence within the study. To provide children with well-matched, highly familiar words, our study also involved repeating stimuli. Importantly, this repetition was consistent across all stimulus categories (W, PW, CS, FF) and all conditions. Moreover, the order of stimulus presentation was randomized, thus controlling for differences in the frequency of repetitions between oddball and base items in each condition and for possible ensuing statistical regularity effects. Consequently, potential statistical responses, if present, would blend into low-frequency background noise, ensuring that our findings remain uncompromised.

For future studies, a longitudinal developmental approach would be of interest. van de Walle de Ghelcke et al. (2020a) did a 1-year follow-up of beginning readers in 1st grade and found an increase in the response strength to letter strings (W or PW) embedded in FF. They also show topographical changes characterized by a transition of peak amplitude from a posterior occipito-medial electrode to a more lateral position (O1 to P7). Their result aligns with descriptions in literature of more posterior VWFA activation in children (Lochy et al., 2016; Olulade et al., 2015) and more lateral letter string responses in adults (Lochy et al., 2015). Follow-ups across longer time scales or cross-sectional studies across a broader age range with multiple testing time points could capture shifts across reading development and compare to studies using more classical ERP paradigms and focusing on the N1 (Fraga-González et al., 2021). Moreover, the effects of reading abilities should be further surveyed within such a longitudinal framework.

5. Conclusion

The present study assessed visual print processing in 2nd- and 3rd-grade PR and TR. The analyses focused on discriminatory responses to oddball stimulus processing over the occipito-temporal cortex. Our contrasts represented discriminations of oddballs along the levels of familiarity (W *vs* PW *vs* CS embedded in FF) and orthographic sensitivity (FF *vs* CS in W). Our results suggest that both TR and PR show coarse visual sensitivity to print. However, the level of this sensitivity response depended on children's reading skills and was less pronounced in PR. Children also showed a basic level of familiarity as reflected in the discrimination of orthographically legal and illegal letter strings (W/PW *vs* CS oddballs), but the more subtle lexicality distinction is still lacking, possibly due to the developmental stage or the rapid visual presentation design. Finally, the differences in the oddball response levels between TR and PR for the conditions and hemispheres may reflect differences in learning and developmental progress between the groups or alternative strategies in PR. The results extend our insights on automatic visual print processing and the influence of reading skills therein. By comparing oddball-base pairs of differing sensitivity (coarse *vs* fine) and of incrementally increasing familiarity (non-lexical and orthographically illegal, non-lexical but legal, orthographically legal and lexical), it delivers more resolved information about the development of sensitivity versus familiarity in early readers.

Ethics statement

The studies involving human participants were reviewed and approved by the *Kantonale Ethikkommission Zürich* (*BASEC No. 2018-01261*). Written informed consent to participate in this study was provided by each participant's legal guardian/next of kin.

Funding

This work was supported by Fondation Botnar (project All-Read, 6066).

Data/code availability and pre-registration statement

The de-identified summary data, experimental material, and analysis scripts for this study are available at https://osf.io/85fv7/. Due to ethical reasons, since neuronal data cannot be fully anonymized, we do not provide the raw individual-level data on a public repository. For access to raw data, please contact the corresponding author for a data sharing agreement. Legal copyright restrictions prevent the public archiving of the behavioral tests described in the Methods section. These materials can be obtained from the copyright holders in the cited references. For any questions or additional material, please contact the corresponding author. Neither the study procedure nor analyses were pre-registered prior to the research being conducted.

Author contributions

CL; conducted data preprocessing, analysis, statistics, and visualizations, and wrote the article. CL, SC; collected the data and were involved in study design and coordination. GFG; provided critical help and feedback to task and script development. SB; provided infrastructure and critical feedback to all stages, study design and coordination, co-wrote the article. All authors critically read and commented on the article.

Submission declaration

This work has not been published and is not being considered for publication elsewhere.

Open practices

The study in this article earned Open Material badge for transparent practices. The materials used in this study are available at: https://osf.io/85fv7/.

Declaration of competing interest

The authors have no competing interest to declare.

Acknowledgments

We are grateful for the support of Fondation Botnar and for the work by S. Schwarz, R. Füzér, I. Karipidis, G. Pleisch, A. Brem, Y. Jin Ressel, M. Röthlisberger, V. Fehr, A. Kressebuch, S. Glutz, I. Bevanda, E. Montevecchi, A. Freihofer, E. Hefti, J. Schiesser, M. Janki, and E. Eichenberger in recruitment, study planning and management, behavioral assessments, and EEG recordings. Finally, we thank all families and their children for participating in this study, we greatly appreciate your efforts.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2023.12.010.

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