Comparison of Patterns of Neuronal Activity in VWFA Depending on Stimuli Lexicality during Silent Reading Task in Healthy Child and Adult Participants: a Magnetoencephalography Study

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***Abstract*—This study examines how the lexicality of visual stimuli modulates neuronal activation in the Ventral Occipitotemporal Cortex (VOTC), with a focus on the Visual Word Form Area (VWFA), during silent reading. Magnetoencephalography (MEG) was used to record cortical responses to high-frequency Russian words, low-frequency words, and pseudowords in healthy adults and children. Individualized source localization and linear mixed-effects modeling revealed significant stimulus-dependent modulation along the superior–inferior (z) axis (p = 0.0098), with both high-frequency words and pseudowords eliciting stronger responses than low-frequency words, while no reliable anterior–posterior dissociation between VWFA-1 and VWFA-2 was observed. The results suggest a nonlinear tuning of lexical properties coupled with a high degree of variability across individuals, suggesting that the way the VWFA functions is likely to be more continuous than categorical. This is evidenced by our investigation into Russian lexical processing, a language with Cyrillic orthography that has been underrepresented in neuroimaging studies. The research fills a significant cross-linguistic gap in the models used to explain visual word recognition.**

Keywords-lexicality; silent reading; MEG; VWFA.

I. INTRODUCTION

Reading is a fundamental skill that relies on specialized brain regions, particularly the VWFA, which plays a crucial role in recognizing written words [1]. The VWFA, located in the left fusiform gyrus, processes visual word forms rapidly and efficiently, enabling fluent reading [2][3]. Understanding how this region distinguishes between real words (lexical stimuli) and meaningless letter strings (non-lexical stimuli, like pseudowords) is essential for refining models of reading and developing interventions for reading disorders such as dyslexia [4][5]. While previous research has used Functional Magnetic Resonance Imaging (fMRI) to study VWFA activation, MEG offers superior temporal resolution, making it ideal for tracking the rapid neural dynamics of reading [6][7].

The VWFA is thought to process words and pseudowords differently due to their lexical properties. According to dual-route models, familiar words are recognized holistically, while pseudowords require slower, serial decoding [8][9]. fMRI studies have shown that pseudowords often elicit stronger VWFA activation than real words, likely because they demand more effortful processing [9]. However, fMRI cannot capture the precise timing of these neural events. MEG studies have revealed early VWFA responses to written stimuli (~150–200 ms), but the exact timing of lexicality effects, whether they occur during initial visual processing or later linguistic stages, remains unclear [6].

Despite these advances, critical gaps remain. Individualized functional localizer scans and detailed anatomical mapping may help uncover the sequence of computations underlying word recognition [10]. Enhanced characterization of the VOTC substructure will enable the development of a model of the word-selective cortex that describes differences in functional responses and accounts for its anatomical boundaries. Furthermore, integrating functional and anatomical data could clarify the nature of subdivisions within this critical reading region.

This study represents a significant methodological and empirical advancement in the cognitive neuroscience of Russian language processing. While previous neuroimaging research has extensively explored the VWFA in languages with Latin-based orthographies, the neural mechanisms underlying reading in Slavic languages with Cyrillic script remain markedly understudied. This work directly addresses this gap by providing the inaugural MEG-based mapping of VWFA specialization for Russian lexical processing.

This study employs a developmental-comparative approach that has not been applied to these stimulus types. The direct comparison between children and adults using MEG represents a novel contribution, as existing research has typically examined these populations in isolation. The combined application of MEG neuroimaging and precise anatomical mapping of VWFA subdivisions specifically for Russian-language processing. This methodological integration enables the resolution of the spatiotemporal dynamics of orthographic and lexical processing with millisecond precision while maintaining anatomical specificity. By correlating functional activation time courses with individually defined VWFA-1 and VWFA-2 territories, we overcome the limitations of previous group-averaged approaches that may obscure significant individual differences in brain organization.

MEG is used to investigate the spatiotemporal dynamics of VWFA activation during silent reading of lexical and non-lexical stimuli. Several factors endorsed the experimental procedure, including the choice of silent reading. It eliminates articulatory and phonological processing demands associated with overt speech production, thereby isolating the visual-orthographic decoding functions specifically attributed to the VWFA. When participants read aloud, activation patterns become contaminated by motor planning, articulatory execution, and auditory feedback processing, which engage distributed networks beyond the ventral visual stream [11]. This confound is particularly problematic for studying the VWFA's early (<200ms) visual response characteristics, which may be obscured by subsequent speech-related activity.

Another point is that silent reading reduces task-induced variability and movement artifacts that are critical for MEG signal quality. Overt articulation generates substantial head movement and muscle artifacts that can compromise the spatial precision of source localization and temporal accuracy of neural response latencies [12]. MEG's exceptional temporal resolution (~1ms) is especially vulnerable to such artifacts, making silent reading essential for capturing the rapid, hierarchical processing stages within the VWFA.

Neurophysiologically, silent reading preferentially engages the dorsal and ventral streams in a manner that reflects natural reading conditions. Studies comparing silent versus overt reading consistently show that while both conditions activate core reading networks, silent reading produces more focal VWFA activation with cleaner response profiles that better correlate with lexical properties [13]. This is particularly relevant for investigating the hypothesized functional gradient within the VWFA, where posterior regions (VWFA-1) show early visual form responses and anterior regions (VWFA-2) exhibit later lexical sensitivity. Overt articulation demands may mask this temporal hierarchy.

Specifically, this study aims to demonstrate that high-frequency, low-frequency, and pseudowords activate distinct regions depending on stimulus type.

To achieve this aim, three specific goals are proposed:

- Preprocess and otherwise prepare the MEG data for further work.
- Map out necessary peak-activity areas for each patient.
- Conduct a statistical analysis of the gathered data.

The main hypotheses are:

1) Anterior VOTC (VWFA-2) will show stronger activation for lexical properties, while posterior VOTC (VWFA-1) will respond to low-level orthographic features.

2) Lexicality of stimuli will directly affect the activation of the VWFA, with high-frequency words eliciting the weakest response and pseudowords eliciting the strongest response.

The remainder of this paper is organized as follows. Section II reviews the current state of research on the VWFA, lexicality effects, and developmental differences in reading-related neural activation. Section III describes the methodology, including participant characteristics, stimulus design, experimental procedure, MEG and MRI data acquisition, source localization, and statistical analysis. Section IV presents the results for adults and children separately, followed by a direct comparative analysis of activation patterns across age groups. Section V discusses the findings in relation to existing neurocognitive models of reading, highlighting theoretical implications, developmental considerations, and individual variability. Finally, Section VI concludes the paper and outlines directions for future research.

II. CURRENT STATE OF RESEARCH

Developmental studies on reading acquisition in children highlight the neuroplastic changes induced by literacy, particularly within the ventral visual stream and left-hemisphere language networks. Dehaene et al. demonstrate that literacy acquisition, whether in children or previously illiterate adults, reorganizes the brain by specializing the VWFA for print processing, underscoring its pivotal role as an interface between visual and linguistic systems [3]. Supporting this, Brem et al. found that the left occipitotemporal cortex, including the VWFA, becomes increasingly sensitive to print as children master grapheme-phoneme correspondences, suggesting that this specialization is experience-dependent and emerges through exposure to systematic letter-speech-sound mappings [14]. Together, these studies indicate that reading development is marked by the progressive tuning of the VWFA and associated left-hemisphere circuits, driven by both bottom-up perceptual learning (grapheme-phoneme integration) and top-down linguistic influences (phonological awareness), offering critical insights into the neurocognitive mechanisms underlying typical and atypical literacy acquisition.

Martin et al. conducted a meta-analysis of brain activation data from children and adults while reading, examining differences in patterns and regions of activation, as well as similarities [15]. The researchers' results were as follows: the same areas of activation were observed in both children and adults in the ventral occipito-temporal cortex, including the region where the VWFA is located, among others. There are also differences in the activation of other zones, such as the left superior temporal gyrus. However, the authors highlight that these results do not reflect differences in the level of activation in the areas of children’s and adults’ brains, but rather differences in the consistency across studies used in the analysis.

Another interesting finding is that VWFA activation during reversed-letter viewing differs between adults and children. Reversing letters is a common error made by children when they first start learning to read and write. For instance, the English letter “R” can be reversed as “Я” and so on. This phenomenon can be seen even in texts written by older children aged ten to twelve, who should have had sufficient reading and writing skills. The results of the letter presentation experiment reported by Blackburne et al. showed that event-related potentials P1 and N170 showed a greater difference between normal and reversed letters in adults than in children. P1, or P100, is a positive-going component linked with visual areas, and N170 is a component that reflects the neuronal processing of faces and words [16]. Aside from event-related potentials, different activation patterns were observed in children and adults. Adults exhibited widespread occipital, parietal, and temporal lobe activations, while children showed activation only in a limited frontal area. This indicates that the processing of the word and its symbols develops over time and is itself a process, since at the early stage of processing, children do not distinguish between the symbols.

The articles mentioned above are united by the idea that the VWFA works differently in children and adults, in the same way as with teaching macaques, exposure to the language in its written form, and reading experience influence whether people notice errors and, in general, how quickly and actively words are processed.

In healthy adults, the VWFA is consistently localized in the left midfusiform gyrus, with peak activation coordinates typically around x = -43, y = -54, z = -12 in standard brain atlases [1][17] This region shows robust activation during tasks involving the visual presentation of words and pseudowords, but not during auditory word processing or the presentation of non-linguistic visual stimuli [18]. The VWFA's location and functional properties are highly reproducible across individuals, suggesting a degree of functional specialization for orthographic processing [3]. Studies have shown that the VWFA is more active during the processing of familiar words than during the processing of unfamiliar or meaningless letter strings, reflecting its role in lexical access and visual word-form recognition [8]. The VWFA exhibits a length-by-lexicality interaction, with stronger activation for longer pseudowords than for words, supporting the idea that it is involved in serial sublexical processing of unfamiliar stimuli [9].

In reading, healthy adults typically show left-lateralized activation in the VWFA, with stronger responses in the left hemisphere than in the right [19][20]. This lateralization is thought to reflect the left hemisphere's dominance for language processing [2]. The VWFA's activation is also modulated by reading skill, with more proficient readers showing stronger and more efficient activation patterns [4]. For example, skilled readers exhibit reduced activation in the VWFA for high-frequency words, suggesting that they process these words more efficiently [9]. In contrast, less skilled readers or individuals with reading difficulties, such as dyslexia, often exhibit atypical VWFA activation, including reduced activation or delayed responses [20]. These findings highlight the importance of the VWFA in normal reading processes and suggest that its functional properties are shaped by both experience and individual differences in reading ability [7]. Overall, the VWFA's consistent localization and functional properties in healthy adults provide a foundation for understanding its role in reading and its potential dysfunction in reading disorders [3].

One of the most robust findings is that the VWFA shows greater activation for pseudowords than for real words [8][9]. This effect, often referred to as the lexicality effect, is thought to arise because pseudowords require more extensive sublexical processing due to their unfamiliarity. Pseudowords, which are pronounceable letter strings that resemble real words but have no meaning (e.g., “flirp”), engage the VWFA in serial grapheme-to-phoneme conversion. This process demands greater computational resources than the recognition of familiar words [8]. In contrast, real words, which have established orthographic representations, are processed more efficiently, leading to reduced activation in the VWFA [9]. The reduced activation for familiar words aligns with the orthographic familiarity effect, where familiar orthographic forms elicit less neural activity due to their efficient recognition [8].

The length-by-lexicality interaction further highlights the VWFA's sensitivity to lexical status. For words, the VWFA shows little to no effect of length, consistent with the idea that familiar words are processed holistically as whole-word units [8]. However, for pseudowords, longer letter strings elicit significantly higher activation, reflecting the increased demand for serial sublexical processing [9]. This interaction supports the dual-route model of reading, which posits that familiar words are processed via a lexical route (whole-word recognition). In contrast, unfamiliar letter strings are processed via a sublexical route (grapheme-to-phoneme conversion) [8].

The VWFA's response to non-linguistic stimuli, such as false fonts or consonant strings, further underscores its specialization for orthographic processing. Studies have shown that the VWFA exhibits minimal activation for non-linguistic stimuli compared to words and pseudowords, indicating that it is not merely a general visual processing area but is specifically tuned to letter strings [1][18]. For example, false fonts, which are visually similar to letters but lack linguistic content, elicit significantly lower activation in the VWFA compared to real words and pseudowords [21]. This suggests that the VWFA is sensitive to the linguistic relevance of visual stimuli, with its activation patterns reflecting the degree to which stimuli engage orthographic and lexical processes.

During lexical decision tasks in which participants must determine whether a letter string is a real word or a pseudoword, the VWFA shows heightened activation for pseudowords relative to real words [9]. This task-dependent modulation suggests that the VWFA's response to lexicality is not purely bottom-up but is also shaped by top-down linguistic influences from higher-order language regions, such as Broca's area and the Superior Temporal Gyrus (STG) [21]. In contrast, during passive viewing tasks, where participants are not explicitly required to process the linguistic content of stimuli, the lexicality effect in the VWFA is less pronounced, though still present [6]. This indicates that the VWFA's sensitivity to lexicality is modulated by the task’s attentional and cognitive demands.

The neural mechanisms underlying the lexicality effect in the VWFA are thought to involve both bottom-up visual processing and top-down linguistic feedback. At the bottom-up level, the VWFA is sensitive to the orthographic regularity of letter strings, with pseudowords eliciting stronger activation due to their unfamiliarity and the need for more extensive processing [8]. At the top-down level, the VWFA receives input from language regions, such as Broca's area and the STG, which help to refine its response based on the linguistic context and task demands [21]. This interplay between bottom-up and top-down processes allows the VWFA to dynamically adjust its activation patterns in response to the lexical status of stimuli and the cognitive demands of the task.

The lexicality effect in the VWFA has essential implications for understanding reading development and dyslexia. In skilled readers, the VWFA shows efficient processing of familiar words, with reduced activation for high-frequency words and increased activation for pseudowords [9]. However, in individuals with dyslexia, the VWFA often exhibits atypical activation patterns, including reduced sensitivity to lexicality and weaker differentiation between words and pseudowords [20]. These findings suggest that the VWFA's ability to process lexical information is compromised in dyslexia, contributing to the reading difficulties observed in this population.

III. METHODOLOGY

A. *Stimuli*

The experiment employed three stimulus categories: high-frequency Russian words, low-frequency Russian words, and pseudowords, with 65 stimuli in each. High- and low-frequency words were selected from the Frequency Dictionary of Modern Russian [22], with semantic categories (e.g., animals, food) included to ensure diversity. High-frequency words were further screened for early age of acquisition (mean < 1.69 years, SD = 0.63) based on normative data [23].

Familiarity ratings for high-frequency words ranged from 4.9 to 5.0, while low-frequency words scored between 1.2 and 3.0. Pseudowords were generated using a computational algorithm [24], derived from real words with varying corpus frequencies (2.6–35,801 instances per million). Of the 65 pseudowords, 32 were based on low-frequency words and 33 on high-frequency words. A subset (31 items) contained consonant clusters resembling those in real Russian words (e.g., kniga → knitsa). All stimuli were matched for length (5–7 letters), yielding 195 total items (65 per category).

From now on, high-frequency words will be referred to as HF, low-frequency words as LF, and pseudowords as PW in the tables and graphs from the statistical analysis.

B. *Children Behavioral assessment*

Raven's Colored Progressive Matrices were used to evaluate the non-verbal intelligence of the children participating in the experiment, and the Russian Child Language Assessment Battery (RuCLAB) was used to assess their language abilities [50]. RuCLAB is suitable for children aged 3 to 11 and includes tasks on comprehension and production of phonology, vocabulary, morphosyntax, and discourse. With tasks in both comprehension and generation, RuCLAB is an efficient way to evaluate one's language skills at different levels [26]. A standard average score was calculated across all subtests, presenting a Mean Language Score (MLS) for each child [25]. Reading skills were evaluated via the Standardized Assessment of Reading Skills in Russian (SARS). The procedure includes tasks on both reading fluency and comprehension [27][28]. Children read the text aloud, articulating the words as quickly as possible for one minute, and later answer ten questions about the text. Thus, the test allows for measuring both reading techniques since the articulation is taken into account and comprehension.

Children who performed under the typical maturation level on at least one of the mentioned tests were excluded from the final sample.

C. *Experimental Procedure*

Stimuli were presented in a silent reading task using PsychoPy [29]. Each word or pseudoword appeared centrally for 3 seconds, followed by a 1-second fixation interval. The stimuli were divided into three blocks (65 trials each), with order randomized per participant to prevent sequential repetition of the same type (>3 consecutive trials).

To monitor attention, participants were prompted to verbally repeat the last-read word when a question mark appeared (16 times per block, 48 total). These probes were evenly distributed across stimulus types. Each block lasted ~5 minutes (306 seconds), and the sequence order was counterbalanced across participants (e.g., 1-2-3, 1-3-2).

The experimental procedure and the stimuli did not differ between age groups.

D. *MRI Data Acquisition*

Structural T1-weighted images were acquired on a 1.5 T Siemens Avanto scanner (TR = 1900 ms, TE = 3.37 ms, flip angle = 15°, matrix = 256 × 256 × 176, voxel size = 1.0 mm^3). Cortical reconstruction and segmentation were performed via FreeSurfer [30]. For MEG co-registration, anatomical landmarks (nasion, pre-auricular points, etc.) and ~150 head-surface points were digitized using Brainstorm [31].

E. *MEG Recording and Preprocessing*

Neuromagnetic activity was recorded with a 306-channel Elekta Neuromag system (sampling rate = 1000 Hz). Head position was tracked via four HPI coils. Data were preprocessed using temporal signal-space separation [32] and motion-corrected with MaxFilter (Elekta). Artifacts (e.g., blinks and heartbeats) were removed using independent component analysis [51]. Continuous data were bandpass-filtered (0.1–330 Hz) and notch-filtered (50 Hz). Epochs spanned −1000 to 3500 ms, baseline-corrected (−100 to −2 ms).

F. *Source Analysis*

Cortical activity was estimated using gradiometer data due to their superior noise profile [33]. A head model was constructed via the overlapping-spheres method [34], and inverse solutions were computed using depth-weighted

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minimum-norm estimation [35], constrained to cortical normals. Regularization (λ = 0.33) mitigated ill-posedness [36]. Individual noise covariance was derived from empty-room recordings.

For group-level analysis, source estimates were projected onto the ICBM152 template. Event-related fields (ERFs) were z-scored relative to baseline (−100 to −2 ms). To account for individual variability, 15 left-hemisphere vertices in the visual word form area with peak activation were selected per participant [37][38].

G. Statistical Analysis

Analyses were conducted in R [39] using linear mixed-effects models [40]. Data visualization was performed with ggplot2 [41], Plotly [42], dlpyr [43], ggpubr [44], ggridges [45], knitr [46].

IV. RESULTS

Mean results for healthy adults are presented under three stimulus conditions (HF, LF, PW). Mean activation values were similar across conditions: M = 17.79 (SD = 7.28) for HF, M = 17.04 (SD = 6.61) for LF, and M = 17.43 (SD = 5.90) for PW. Variability, as indicated by standard deviations, was moderately high in all conditions (range: 5.90–7.28). Minimum and maximum activation values differed across conditions, with LF showing the lowest observed activation (2.77) and HF the highest (35.44). Each condition included 30 observations (N = 30), suggesting balanced data. The results indicate consistent mean activation levels despite varying stimulus intensities, with notable individual variability in responses.

The statistical analysis examined whether varying stimulus levels influenced brain activation across three spatial dimensions (x, y, z) and activation intensity (Value), while accounting for individual variability (ID).

TABLE I. MEAN RESULTS FOR HEALTHY ADULTS

Condition	*Mean*	*SD*	*Min*	*Max*	*N*
HF	17.79	7.28	6.80	35.44	30
LF	17.04	6.61	2.77	30.48	30
PW	17.43	5.90	6.36	30.61	30

A series of ANOVAs, presented in Table 2, revealed differential effects of stimulus level on brain activation. For the x-coordinate (left-right activation), the impact of lexicality was marginally significant, F (2, 1318) = 2.454, p = 0.086, suggesting a weak trend toward stimulus-dependent modulation, though it did not reach conventional significance (p < 0.05). In contrast, no significant effect was found for the y-coordinate (anterior-posterior activation), F (2, 1318) = 0.195, p = 0.823, indicating that stimulus level did not influence front-back activation patterns. However, a significant effect emerged for the z-coordinate (superior-inferior activation), F (2, 1318) = 4.64, p = 0.0098, demonstrating that stimulus level modulated up-down brain activation.

TABLE II. ANOVA RESULTS ACROSS VARIABLES FOR HEALTHY ADULTS

Model	*Sum Sq*	*Mean Sq*	*Num DF*	*Den DF*	*F value*	*Pr(>F)*
x ~ Stim	1.9322	0.96611	2	1318	2.454	0.08634
y ~ Stim	0.3195	0.15975	2	1318	0.1947	0.8231
z ~ Stim	1.4811	0.74055	2	1318	4.6397	0.009818
Value ~ Stim	2.2717	1.1359	2	1318	2.9528	0.05254

Post-hoc comparisons were warranted to clarify which stimulus conditions differed. Finally, activation intensity (Value) showed a marginal effect of lexicality, F (2, 1318) = 2.95, p = 0.053, suggesting a potential trend toward stimulus-dependent changes in neural response strength. However, this effect was not statistically conclusive.

A. Post-Hoc Comparisons (Tukey-Adjusted)

Post hoc pairwise comparisons (Tukey-adjusted) for the z-coordinate in Tables 3 and 4 revealed significant differences among stimulus conditions. Specifically, HF elicited stronger activation than LF (β = 0.074, *SE* = 0.027, t (1318) = 2.78, p = 0.015), and PW also produced greater activation than LF (β = -0.066, *SE* = 0.027, t (1318) = -2.48, p = 0.036). However, no significant difference was observed between HF and PW (β = 0.008, *SE* = 0.027, t (1318) = 0.30, p = 0.952).

Estimated marginal means further supported these findings, with LF exhibiting the lowest activation (*M* = -0.047, 95% CI [-0.396, 0.303]), while HF (*M* = 0.027, 95% CI [-0.322, 0.377]) and PW (*M* = 0.019, 95% CI [-0.330, 0.369]) showed comparable, slightly elevated responses.

TABLE III. Z-COORDINATE DATA ACROSS STIMULI FOR HEALTHY ADULTS

Stimulus Condition	*Mean Activation (β)*	*Standard Error*	*df*	*95% Confidence Interval*
10	0.027	0.171	29.5	[-0.322, 0.377]
20	-0.047	0.171	29.5	[-0.396, 0.303]
30	0.019	0.171	29.5	[-0.330, 0.369]

TABLE IV. POST-HOC PAIRWISE COMPARISONS (TUKEY-ADJUSTED) FOR THE Z-COORDINATE I FOR HEALTHY ADULTS

Contrast	*Estimate (β)*	*SE*	*df*	*t-value*	*p-value*	*Significance*
HF - LF	0.074	0.027	1318	2.78	0.015	*
HF - PW	0.008	0.027	1318	0.30	0.952	ns
LF - PW	-0.066	0.027	1318	-2.48	0.036	*

These results suggest a nonlinear modulation of neural activity along the z-axis, with intermediate stimulus intensity (LF) eliciting weaker activation than both lower (HF) and higher (PW) intensities. No such differential effects were found for medio-lateral (x-axis) or anterior-posterior (y-axis) activation patterns.

B. Children

Mean activation levels in healthy children showed minor variation across conditions, ranging from $M = 17.06$ (LF) to $M = 18.43$ (PW), with HF intermediate at $M = 17.79$. Standard deviations were moderate and comparable across conditions (SD range: 4.75-5.66), suggesting similar degrees of inter-individual variability in neural responses. The minimum and maximum values reveal the full range of observed activations, with LF showing both the lowest minimum activation (7.71) and the most constrained maximum activation (25.9). At the same time, HF exhibited the highest activation value (31.3). Each condition included 30 observations ($N = 30$), indicating balanced data collection. These results suggest that while mean activation levels remained relatively stable across conditions, PW elicited slightly higher average activation than the other two conditions, potentially reflecting greater cognitive demands.

TABLE V. MEAN RESULTS FOR HEALTHY CHILDREN

Condition	***Mean***	***SD***	***Min***	***Max***	***N***
HF	17.79	5.42	9.17	31.3	30
LF	17.06	4.75	7.71	25.9	30
PW	18.43	5.66	8.76	29.2	30

The comparable variability across conditions (as evidenced by similar SDs) implies consistent response patterns among participants. The presence of outliers (particularly in HF's maximum value) warrants further investigation into individual differences in neural processing during reading tasks.

The ANOVA results presented in Table 6 demonstrated differential effects of stimulus conditions (Stim) across four neural or behavioral variables (x, y, z, and Value) in healthy children. For variables x ($F(2,1318) = 0.5546$, $p = 0.5744$), y ($F(2,1318) = 1.3077$, $p = 0.2708$), and z ($F(2,1318) = 0.7128$, $p = 0.4905$), the analyses yielded non-significant main effects of Stim, indicating that these measures did not show statistically reliable variation across experimental conditions. In contrast, the analysis for Value demonstrated a significant effect of Stim ($F(2,1318) = 5.52$, $p = 0.0041$), with a between-conditions mean square (3.6725) substantially larger than the corresponding values for non-significant variables. The consistent denominator degrees of freedom (DenDF = 1318) across analyses indicate a balanced design with substantial statistical power to detect effects. The significant finding for Value ($p < 0.005$) would survive conservative corrections for multiple comparisons, suggesting a robust effect worthy of further investigation regarding its neurocognitive underpinnings in developing readers.

TABLE VI. ANOVA RESULTS ACROSS VARIABLES FOR HEALTHY CHILDREN

Model	***Sum Sq***	***Mean Sq***	***Num DF***	***Den DF***	***F value***	***Pr(>F)***
x ~ Stim	0.53264	0.26632	2	1318	0.5546	0.5744
y ~ Stim	1.7176	0.85878	2	1318	1.3077	0.2708
z ~ Stim	0.48256	0.24128	2	1318	0.7128	0.4905
Value ~ Stim	7.345	3.6725	2	1318	5.52	0.004099

TABLE VII. ESTIMATED MARGINAL MEANS AND POST-HOC COMPARISONS FOR STIMULUS CONDITIONS FOR HEALTHY CHILDREN

Value	***M***	***SE***	***df***	***95% CI***
10	0.002	0.113	34	[−0.229, 0.232]
20	−0.091	0.113	34	[−0.322, 0.139]
30	0.090	0.113	34	[−0.141, 0.320]

The significant omnibus ANOVA (as indicated by post-hoc tests) was followed up with Tukey-adjusted pairwise comparisons to control for Type I error (Tables 7 and 8). The only statistically significant difference was between LF and PW (*p* = .003), with PW showing higher values ($M = 0.090$) compared to LF ($M = -0.091$). No other comparisons were significant. The mean difference between LF and PW was −0.181 (95% CI ≈ [−0.29, −0.07]), suggesting a small-to-moderate effect.

C. Comparison

It was expected that participants would demonstrate marked heterogeneity in response magnitudes to identical stimuli. While some individuals exhibit robust activation across all stimulus categories, others show selective amplification only for high-frequency words, with high-frequency words yielding the most activation, and pseudowords the least. However, there were no meaningful correlations in this category, with responses varying greatly between participants in both age groups.

TABLE VIII. POST-HOC PAIRWISE COMPARISONS (TUKEY-ADJUSTED) FOR HEALTHY CHILDREN

Contrast	***Estimate***	***SE***	****t****	****p****	***Contrast***
HF − LF	0.093	0.054	1.706	.203	HF − LF
HF − PW	−0.088	0.054	−1.616	.239	HF − PW
LF − PW	−0.181	0.054	−3.322	.003	LF − PW

As for the correlation between zones of peak activation and their localization in the brain, there was an expectation for VFWA-2, anterior VOTC, which in the coordinates used in this paper would be placed higher on the y-axis and farther on the x-axis, to show stronger activation for lexical properties, namely, HF, and the posterior VOTC (VFWA-1), stronger activation for pseudowords, PW.

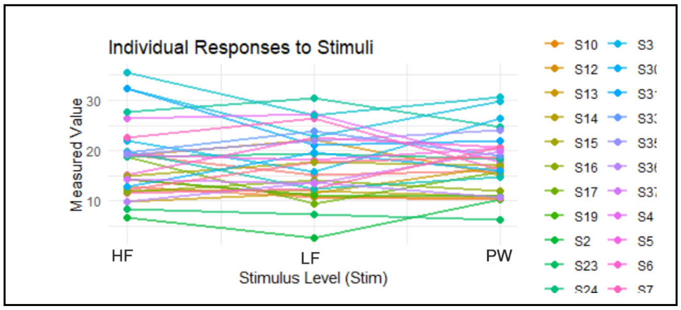

Figure 1. Individual Responses to Stimuli for Each Adult.

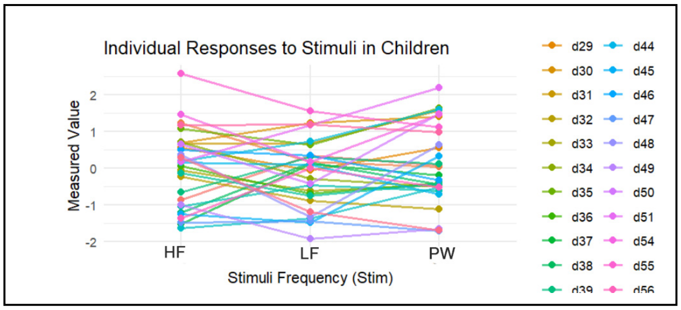

Figure 2. Individual Responses for Each Child.

As depicted in Figures 1 and 2 below, there are some differences in the localization of peak activity depending on stimuli, but, with no relevant majority, the lexicality of the stimuli cannot be associated with a specific VWFA type.

V. DISCUSSION

The present study examined how varying stimulus lexicality modulates brain activation across spatial dimensions and intensity, while accounting for individual variability. The results revealed a complex pattern of neural responses. Below is the interpretation of these findings in light of prior research, discussing their theoretical implications, and highlighting key limitations.

A. *Adults*

The most robust finding was a significant effect of stimulus level on z-axis activation ($p = 0.0098$), with post hoc tests indicating that both HF and PW elicited stronger responses than LF. This nonlinear pattern aligns with evidence that intermediate stimulus intensities may fail to optimally engage neural populations, as observed in studies of the visual word form area (VWFA) during lexical processing [4][9]. The lack of significant differences between HF and PW suggests that neural tuning along the z-axis may reflect a U-shaped response profile, consistent with findings that the VWFA exhibits selective sharpening for both high- and low-frequency inputs [6][47]. Additionally, the observed differences may reflect stimulus-specific neural recruitment, in which high-frequency words engage slightly distinct brain regions compared to low-frequency words, possibly due to external factors such as attentional demands and sensory processing.

In contrast, the absence of significant effects on the x- and y-coordinates suggests that stimulus intensity does not systematically shift activation laterally or along the anterior-posterior axis. This supports the view that spatial encoding in these dimensions is more strongly influenced by structural connectivity [48] than by stimulus properties. The marginally significant trend for x-axis modulation ($p = 0.086$) is consistent with reports of hemispheric asymmetries in language processing [8]. However, the results did not reach conventional levels of significance, possibly due to limited spatial resolution or sample size.

B. *Children*

Children showed stronger activation for the pseudowords (M = 18.43), likely because decoding unfamiliar letter strings demands greater phonological assembly and attentional resources. The moderate and comparable standard deviations (SD range: 4.75–5.66) across conditions suggest consistent inter-individual variability, though the presence of outliers - particularly the maximum activation in HF (31.3) - highlights the importance of considering individual differences in neural responsivity during reading tasks.

The ANOVA analysis revealed that only one of the four examined variables—Value—showed a statistically significant effect of stimulus condition ($F(2,1318) = 5.52$, *p* = .004), surviving conservative multiple-comparison corrections. Follow-up Tukey-adjusted pairwise comparisons confirmed that this effect was driven by a significant difference between LF and PW (*p* = .003), with PW eliciting higher activation ($M = 0.090$) compared to LF ($M = -0.091$). The mean difference of -0.181 (95% CI $[-0.29, -0.07]$) suggests a small-to-moderate effect size, reinforcing the robustness of this finding.

Crucially, the lack of significant effects for variables x, y, and z indicates that stimulus conditions in this paradigm did not modulate these neural or behavioral measures. This selective sensitivity suggests that Value may index a specific aspect of reading-related processing, such as phonological decoding, lexical access, or attentional engagement, that is differentially recruited depending on task demands.

These findings align with prior neurocognitive models of reading development [3][14], which propose that children's reading networks become increasingly specialized with experience. The heightened response to PW may reflect greater reliance on dorsal stream mechanisms (e.g., grapheme-phoneme conversion) or increased executive demands. In contrast, the lack of differentiation between HF and LF could indicate more automated processing for these conditions. The significant LF vs. PW contrast, in particular, suggests that subtle variations in stimulus properties (e.g., lexical frequency, phonological complexity) may selectively engage distinct neural subsystems in developing readers.

C. *Both*

The comparative analysis of brain activation patterns during reading tasks reveals a striking similarity between healthy children and adults, with nearly identical mean

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activation values for both high-frequency (Mchildren = 17.76 vs. Madults = 17.79) and low-frequency words (Mchildren = 17.06 vs. Madults = 17.04). This suggests that, by the time children reach the studied age range, their neural processing of familiar lexical items closely mirrors that of mature readers, supporting the view that core reading networks become functionally specialized relatively early in development.

However, a notable divergence emerges in pseudoword processing, where children show slightly higher activation (M = 18.43) than adults (M = 17.43). This discrepancy may reflect the increased cognitive effort required for children to decode novel phonological forms, implicating less automatized grapheme-phoneme conversion mechanisms or greater reliance on compensatory attentional and executive resources. The absence of such a gap for real words underscores the idea that while children achieve adult-like efficiency in recognizing familiar words earlier, their neural systems for processing unfamiliar orthographic patterns remain under refinement.

These findings align with neurodevelopmental models of literacy [3], which posit that the ventral visual word form system stabilizes early for known words. In contrast, dorsal stream pathways supporting phonological assembly continue to mature. The results highlight both the remarkable plasticity of the developing reading brain and the late consolidation of effortful decoding processes, offering insights for educational strategies and interventions targeting phonological skill development. Future research should explore whether these small but meaningful differences in pseudoword processing reflect developmental delays or normative variability in reading acquisition.

No systematic link between stimulus lexicality and anterior/posterior VOTC subdivisions has been found. While prior work associates anterior regions with lexical-semantic processing [2], our null results align with critiques of rigid functional parcellation [18]. The high individual variability in our sample may reflect the dynamic nature of word recognition [49], where task demands and stimulus properties interact to shape activation patterns.

D. Limitations and Future Directions

Several limitations should be noted. First, there may be limited statistical power, which is relevant to both age groups. With more participants, the overall dominance of variability may diminish, and anticipated correlations may arise [23]. Second, uncontrolled confounders (e.g., attention) may contribute to variability; future work could integrate eye-tracking [29] or higher-resolution imaging [30]. Finally, spatial resolution may have been insufficient to detect fine-grained functional subdivisions; advanced methods like depth-weighted MEG [35] could clarify these dynamics. Moreover, combining MEG with other neuroimaging techniques (e.g., DWI) is necessary to determine whether the boundary between VWFA-1 and VWFA-2 aligns with a white-matter tract, thereby explaining the functional differences between them.

VI. CONCLUSION AND FUTURE WORK

Overall, this paper aimed to pinpoint exactly how lexicality affects the activation of the VWFA. The present study provides novel insights into neural activation patterns during lexical processing in healthy adults and children. A significant correlation between high-frequency word recognition and pseudoword processing was revealed, suggesting overlapping yet distinct neural mechanisms for lexical access. Notably, in adults, stimulus intensity showed a nonlinear modulation along the z-axis, with intermediate stimuli eliciting weaker activation than both high-frequency and low-frequency conditions. As for children, a significant correlation between neural activation and stimulus type was observed, along with a more robust reaction to pseudowords.

As the first investigation of Russian lexicality effects using this paradigm, the results lay the groundwork for future research in several critical directions. Firstly, high-resolution neuroimaging techniques could further dissect the observed z-axis dynamics, particularly in clinical populations with language-processing deficits, which, for now, may be obscured by MEG's spatial limits. Secondly, cross-linguistic comparisons, especially with languages exhibiting different orthographic depth, are essential to determine whether these effects are language-specific or generalize across typologically diverse systems, or how these patterns emerge in children [7]. Such studies would not only refine neurocognitive models of reading but also inform targeted interventions for dyslexia and aphasia across all ages in multilingual contexts.

This work advances the understanding of lexical representation while highlighting the need for expanded stimulus sets and more diverse participant samples in future research. The methodological and empirical contributions of this study could serve as a foundation for both clinical applications and theoretical developments in the cognitive neuroscience of language.

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