Comparison of Patterns of Neuronal Activity in VWFA Depending on Stimuli Lexicality During Silent Reading Task in Healthy Adults: a Magnetoencephalography Study

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I completed my Bachelor's degree at the Higher School of Economics (HSE), where I specialized in Fundamental and Computational Linguistics with a focus on psycho- and neurolinguistics. My academic path integrated advanced coursework in brain–language relationships with hands-on research at the Center for Language and Brain, including MEG studies of lexical processing and cognitive decline. I have developed strong quantitative and programming skills (R, Python, MATLAB), alongside experience with linguistic corpora, experimental design, and multimodal annotation.

I am now a student of University of Potsdam, in International Clinical and Experimental Linguistics (MA), where I aim to further explore the neural and cognitive mechanisms underlying language processing and preservation.

Current research interests

Neural basis of language processing
Reading acquisition and developmental disorders (dyslexia)
Neuroplasticity and literacy
Multilingualism and the brain

Introduction & Background

The Visual Word Form Area (VWFA)

VWFA is a key brain region for reading, located in the left fusiform gyrus (ventral occipitotemporal cortex - VOTC).

- **Function:** Rapidly recognizes written words and letter strings.
- **Key Question:** How does this region distinguish between real words and pseudowords? (**lexicality effect)**

Prior Findings:

- **fMRI:** Pseudowords often elicit stronger VWFA activation than real words, suggesting more effortful processing.
- **Hypothesized Gradient:** Posterior VWFA (VWFA-1) may handle low-level orthography, while anterior VWFA (VWFA-2) may be sensitive to lexical properties.

The Gap:

- fMRI lacks the temporal precision to track the rapid dynamics of reading.
- MEG offers millisecond resolution, ideal for studying these fast neural processes.
- The neural mechanisms of reading in **Russian (Cyrillic script)** are markedly understudied.

Research Aim & Hypotheses

Aim:

To investigate the spatiotemporal dynamics of VWFA activation during silent reading of stimuli with varying lexicality (high-frequency words, low-frequency words, pseudowords) in healthy adults using MEG.

Main Hypotheses:

1. **Functional Gradient:**
   - **VWFA-2 (Anterior VOTC):** Stronger activation for lexical properties (real words).
   - **VWFA-1 (Posterior VOTC):** Stronger response to low-level orthographic features (pseudowords).
2. **Lexicality Effect on Activation Strength:**
   - **High-Frequency Words:** Weakest response (efficient, holistic processing).
   - **Pseudowords:** Strongest response (effortful, serial decoding).

Methodology

Participants:

- 30 healthy, right-handed Russian-speaking adults.
- Participants provided informed consent in accordance with ethical guidelines approved by the Higher School of Economics ethics committee.
- Children's data also collected and analyzed for comparison, but adults are the primary focus.

Stimuli:

- **195 total items** (65 per condition), matched for length (5-7 letters).
- **High-Frequency Words (Stim10):** Familiar, early age of acquisition (e.g., *kniga* 'book').
- **Low-Frequency Words (Stim20):** Unfamiliar, lower familiarity ratings (e.g., rare animal names).
- **Pseudowords (Stim30):** Pronounceable, meaningless letter strings generated with Wuggy [24] (e.g., *knitsa* from *kniga*).
  a. G enerated using the Wuggy pseudoword generator, which creates pronounceable nonwords matched to real words on subsyllabic structure. Half were derived from high-frequency base words and half from low-frequency base words.

Methodology

Experimental task: Silent Reading

- Stimulus on screen for 3s, followed by 1s fixation.
- Attention checks: Participants verbally repeated the last word when a "?" appeared.
- Rationale: Isolates visual-orthographic processing, minimizes movement artifacts from overt speech [11, 12].

Data Acquisition:

- **MEG:** 306-channel Elekta Neuromag system (1000 Hz sampling rate).
- **MRI:** Structural T1 (1.5T Siemens) for source modeling.

Preprocessing:

- Signal-space separation (MaxFilter), ICA artifact rejection (blinks, heartbeats).
- Epochs: -1000 to 3500 ms, baseline corrected (-100 to -2 ms).
  -

Data Analysis

Source Analysis:

- **Head Model:** Overlapping-spheres method.
- **Inverse Solution:** Depth-weighted minimum-norm estimation, constrained to cortical surface.
- **Individual Definition:** For each participant, the 15 most active vertices in the left-hemisphere VWFA were manually selected.

Statistical Analysis:

- **Linear Mixed-Effects Models** in R.
- Activation levels and peak coordinates (x, y, z) were modeled as functions of stimulus type (Stim10, Stim20, Stim30).
- **Random Effect:** Participant (ID) to account for individual variability.
- **Post-hoc:** Tukey-adjusted pairwise comparisons.

Results

Descriptive Statistics & Activation Strength

- **Similar Means, High Variability** - The average activation levels across all three conditions are remarkably similar (ranging from 17.04 to 17.79). This suggests that, at a gross level, all stimulus types engage the VWFA to a comparable degree. The large standard deviations (approx. 34-41% of the mean) highlight substantial inter-individual differences in neural responsivity, justifying our person-specific analytical approach.
- **Range Reveals Individual Differences** - The minimum and maximum values show that while some participants had very low responses to low-frequency words (2.77), others responded robustly. This variability suggests that low-frequency words, in particular, may be processed very differently depending on the individual's lexicon and reading strategy.
- **Key Implication** - The lack of difference in *mean amplitude* indicates that simply measuring activation is insufficient. To understand lexicality effects, we must examine *where* (spatially) and *when* (temporally) the activation occurs within the VWFA.

TABLE I.   MEAN RESULTS FOR HEALTHY ADULTS

Condition	Mean	SD	Min	Max	N
Stim10	17.79	7.28	6.80	35.44	30
Stim20	17.04	6.61	2.77	30.48	30
Stim30	17.43	5.90	6.36	30.61	30

Spatial Effects in Adults

- **Key Finding: z-axis Specificity** - Stimulus lexicality significantly modulates activation along the **superior-inferior (z) axis** (p = 0.0098). Crucially, there was **no effect on the anterior-posterior (y) axis** (p = 0.823). This directly contradicts Hypothesis 1, which predicted a functional gradient along the y-axis (VWFA-1 vs. VWFA-2).
- **Post-Hoc Analysis (z-axis)** - To understand the nature of the z-axis modulation, Tukey-adjusted pairwise comparisons between the three conditions was conducted.

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

Spatial Effects in Adults

TABLE III.   TABLE 3. 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
Stim10 - Stim20	0.074	0.027	1318	2.78	0.015	*
Stim10 - Stim30	0.008	0.027	1318	0.30	0.952	ns
Stim20 - Stim30	-0.066	0.027	1318	-2.48	0.036	*

The post-hoc tests reveal a surprising **U-shaped pattern**:

- **Stim10 (High-Freq) > Stim20 (Low-Freq)** (p = 0.015)
- **Stim30 (Pseudo) > Stim20 (Low-Freq)** (p = 0.036)
- **Stim10 vs. Stim30** showed **no difference** (p = 0.952).

This reveals a **U-shaped, nonlinear response pattern** along the superior-inferior axis. Intermediate stimuli (low-frequency words) elicited the weakest response, contradicting the linear hypothesis (High-Freq < Low-Freq < Pseudo).
Instead, low-frequency words (Stim20) occupy a unique "processing valley."
They may be too unfamiliar for efficient holistic processing (lexical route) but too "word-like" to trigger the full sublexical decoding engaged by pseudowords, resulting in a weaker net neural response.

Hypothesis overview

Hypothesis 1 (Functional Gradient): REJECTED

- No systematic link was found between stimulus lexicality and anterior/posterior (VWFA-1/VWFA-2) subdivisions. This contradicts the rigid functional gradient hypothesis [2] and aligns with critiques of strict parcellation [18].
- High individual variability was observed, suggesting a more continuous and dynamic functional organization.

Hypothesis 2 (Activation Strength): PARTIALLY SUPPORTED

- Pseudowords (Stim30) did not show the strongest response overall (compared to Stim10), but both showed stronger activation than low-frequency words.
- The **"weaker response to low-frequency words"** is a novel finding.

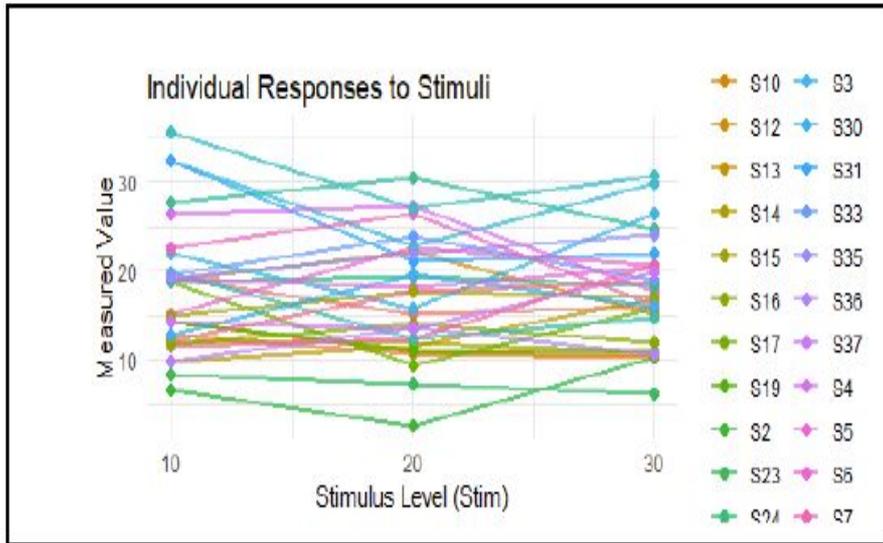# Hypothesis Testing & Individual/Developmental Data

Figure 1. Individual Responses to Stimuli for each adult

High Individual Variability - Some individuals show the expected pattern (e.g., pseudowords > words), while others show the opposite or the U-shaped group average. This underscores the importance of person-specific analyses and suggests that multiple processing strategies can lead to successful reading.

A parallel analysis was conducted on a sample of children to explore developmental trajectories.

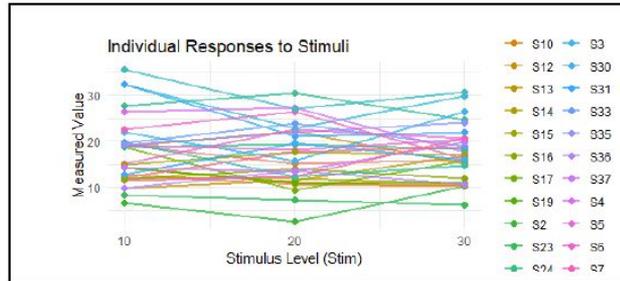# Hypothesis Testing & Individual/Developmental Data

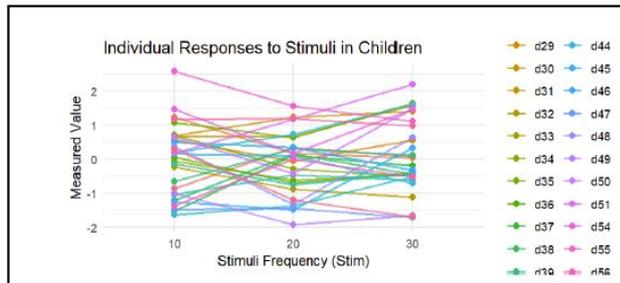Figure 1.   Individual Responses to Stimuli for each adult

Figure 2.   Individual Responses for each child

Unlike adults, children showed a **significant effect on activation Value (p = 0.004)** , with pseudowords (Stim30) eliciting stronger responses than low-frequency words (Stim20). They did **not** show the z-axis spatial modulation observed in adults.

This suggests a developmental shift. Children may rely on **amplitude-based differentiation** (pseudowords simply require more "neural work"), while adults, with more refined systems, show **spatially tuned differentiation** (different stimulus types engage subtly different neural populations within the VWFA, even if overall amplitude is similar). This shift may reflect the consolidation of orthographic representations with reading experience.

Discussion & Limitations

Main Takeaways:

- This first MEG study of Russian reading reveals a complex, nonlinear picture of VWFA function. The key findings are:
  - (1) a **U-shaped response profile** along the superior-inferior axis
  - (2) the **rejection of a rigid anterior-posterior functional gradient**. This challenges simple models of VWFA organization.
- **The** findings support models where the VWFA is a dynamic interface shaped by bottom-up visual features, top-down linguistic feedback, and individual experience. The absence of a simple y-axis gradient suggests that functional specialization is more continuous and interactive than categorical.
- By studying Russian (Cyrillic), this work extends the empirical base of reading research beyond Latin-based languages, showing that core principles of VWFA function may generalize, while also revealing language-specific nuances like the observed z-axis modulation.

Limitations & Future Directions:

- **Statistical Power:** Replication with larger samples is needed.
- **Spatial Resolution:** MEG's spatial resolution may limit detection of fine-grained subdivisions.
- **Confounds:** Uncontrolled factors like attention may contribute to variability.
- **Future Work:**
  - Combine MEG with **diffusion-weighted imaging (DWI)** to see if functional boundaries align with white matter tracts.
  - Use higher-resolution imaging techniques.
  - Expand to cross-linguistic and clinical populations (e.g., dyslexia).

Future Directions - Three priority paths emerge:

1. **Combine MEG with DWI** to test if functional boundaries align with structural (white matter) connectivity.
2. **Study clinical populations** (e.g., dyslexia) to see if this nonlinear pattern is disrupted.
3. **Cross-linguistic comparisons** with non-alphabetic scripts to test universality.

Conclusion

- This first MEG study of lexical processing in **Russian** provides novel insights into VWFA function.
- It reveals a **nonlinear modulation of neural activity** along the superior-inferior (z) axis by stimulus lexicality in adults.
- It challenges the hypothesis of a **rigid anterior-posterior functional gradient** within the VOTC.
- High individual variability underscores the need for **person-specific analyses** in neuroimaging.
- The study establishes a critical **cross-linguistic foundation** for models of visual word recognition, extending beyond Latin-based orthographies.

Next Steps:

- Investigating these dynamics in **dyslexia**.
- Exploring how **white matter connectivity** shapes these functional responses.