

RESEARCH REPORT

Language Localization From Magnetoencephalography (MEG) Beta-Power Dynamics During Sentence Completion

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ABSTRACT

For noninvasive language mapping, the choice of imaging method, task, and baseline remains an area of active research. While the sentence completion task is a recommended option for fMRI studies, the indirect nature of the signal is a limitation of the imaging method. This study presents a sentence completion paradigm for group- and individual-level language localization and lateralization based on beta power (17–25 Hz) modulations. MEG recordings of 21 neurologically healthy native Russian speakers were used to test whether the task would elicit beta desynchronization in canonical language regions during sentence completion. In addition to the traditional passive (no-task) control condition, an active (syllable repetition) control condition was used to further control for nonrelevant processes. The paradigm revealed the engagement of anterior and posterior language-related brain areas using both active and passive control conditions. However, the active control condition provided more widespread activity patterns, suggesting its superior suitability for further individual presurgical language mapping. Despite the individual variability in the results, their general agreement with the current understanding of the language-associated brain topography supports the potential of the developed MEG paradigm for presurgical language mapping.

1 | Introduction

The planning of brain lesion resection in language-eloquent areas commonly relies on presurgical language mapping in order to minimize post-surgery language deficits (Duffau 2023). However, presurgery language mapping is a complex procedure as it demands effective linguistic tasks that activate functionally important language areas in the brain, measured with an appropriate neuroimaging method with high temporal and spatial resolution.

The sentence completion (SC) task has been proposed as an effective task for fMRI presurgery language localization (Black et al. 2017). During the procedure, a person hears or reads a sentence with the last word missing and has to produce a semantically and grammatically correct word to complete the sentence (Ojemann and Mateer 1979). In contrast to other language mapping tasks (i.e., picture naming, word repetition, etc.), the SC task is meant to activate the entire language system (Barnett et al. 2014; Dragoy et al. 2020; Elin et al. 2022), allowing effective and reliable mapping of all potential language-related

Abbreviations: fMRI, functional MRI; MEG, magnetoencephalography; MFG, middle frontal gyrus; MNI, Montreal Neurological Institute; MRI, magnetic resonance imaging; MTG, middle temporal gyrus; ROI, region of interest; SC, sentence completion; SSS, signal space separation; STG, superior temporal gyrus; TOI, time of interest.

regions (Elin et al. 2022; Wilson et al. 2017). Typically, the regions occupy areas in the lateral frontal, temporal, and parietal areas of the left hemisphere (Hertrich et al. 2020) and are involved in hierarchical language processing at different linguistic levels, including phonology, vocabulary, morphosyntax, and semantics in both production and comprehension. We define “language areas” as both the “core” (posterior parts of the inferior and middle frontal gyri, superior and middle temporal gyri) and “margin” (sensorimotor cortex, angular and supramarginal gyri) language areas after Hertrich et al. (2020).

Elin et al. (2022) have developed and validated a Russian language version of the SC task and demonstrated its applicability to study presurgery language mapping using fMRI. Furthermore, considering the importance of the baseline condition, in order to isolate higher-order processes of interest Elin et al. (2022) have compared syllable and pseudoword repetition tasks as two control conditions. The pseudoword repetition task elicited robust and reliable activity but a longer response time in a group of neurologically healthy participants, which could reflect greater task complexity in comparison with syllable repetition (Elin et al. 2022). For this reason, the authors concluded that syllable repetition, as a less complex task, could be a better choice for presurgery fMRI language mapping in patients with existing cognitive deficits (Elin et al. 2022).

Despite the widespread use of fMRI, it has been shown that even minor brain impairments can lead to neurovascular uncoupling (Agarwal et al. 2016), making the method potentially less optimal for language mapping under certain conditions. Additionally, its limited temporal resolution restricts the study of more dynamic brain processes, with potential implications for validity. Specifically, the discrepancy between the temporal resolution of the fMRI in the order of seconds and the rapid brain dynamics increases uncertainty about which processes we are able to detect and decreases the validity of conclusions we can make about the data. Thus, the recording of magnetic activity of neuronal populations with magnetoencephalography (MEG) could be a valuable addition as MEG registers neural activity directly and allows us to identify anatomical structures engaged in language processing with higher validity and better temporal resolution (Lee et al. 2006; Roos and Piai 2020). MEG has already demonstrated a sufficient level of consistency with the traditional Wada test for language lateralization (Bowyer et al. 2020; Youssofzadeh et al. 2020). Therefore, due to the combination of high spatial and temporal resolution, MEG is a promising method for presurgery language mapping (Bowyer et al. 2020).

In order to study the electromagnetic modulations that correspond to lexical and combinatorial processing, Piai et al. (2015) proposed a modification of the SC task, that is, a “context-driven picture naming” task. Herein, the participants were presented with a sentence context, where the last word was replaced by a picture. The task was to read or hear the sentence and name the picture as it appeared. In this and the following MEG studies by Piai et al., while performing context-driven picture naming, the authors registered a consistent beta desynchronization in left anterior and posterior temporal areas, left inferior frontal cortex, and bilateral ventral premotor cortex in neurologically healthy participants and in stroke survivors (Roos and

Piai 2020; Piai et al. 2015; Piai et al. 2014). The listed regions are commonly associated with lexical access (Hanslmayr et al. 2012) and articulatory planning (Piai et al. 2014). Thus, the alignment between the observed sources of activity with the traditional “language areas” supports the further development of the methodology and the paradigm for complex MEG-based language mapping.

On the electrophysiological level, the rhythmic activity of neuronal populations (so-called “brain oscillations”) in the various frequency bands is associated with distinct cognitive operations (Bastiaansen and Hagoort 2006; Sauseng and Klimesch 2008). In particular, oscillations in the beta-frequency band (15–30 Hz) play an important role in both language production and comprehension (Youssofzadeh et al. 2020; Wang et al. 2012; Zioga et al. 2023). Specifically, within the framework of context-driven picture naming, lexical access is initiated prior to the picture onset, already during the processing of the sentence context (Piai et al. 2015). This early planning was reflected in alpha and beta desynchronization, suggesting the role of these oscillatory frequencies in conceptual and lexical retrieval (Roos and Piai 2020; Piai et al. 2015). Subsequently, the authors added a secondary attention-related task that allowed them to isolate and demonstrate that the beta desynchronization corresponded to the linguistic processing but not to attention shifts (Roos and Piai 2020). Hence, data from the previous studies speak in favor of beta desynchronization as a signature of linguistic processing.

Although the context-driven picture naming task is an approximation of daily-life language production and comprehension (Griffin and Bock 1998), it does not fully require spontaneous speech as the SC task does. The aim of this work was to apply the existing Russian-language SC task (Elin et al. 2022) for MEG language localization and lateralization in order to overcome the limitations of fMRI language mapping. Similar to Elin et al. (2022), we aimed to implement the syllable repetition baseline as an active condition to control for the nonspeech-specific information processing in addition to the passive control condition traditionally used in MEG studies (i.e., intertrial interval with no task).

Thus, in the present work, we expected to register significant beta desynchronization during the SC task, becoming more widespread over time as the unfolding sentence should involve more processing. We conducted a group-level analysis to explore the general ability of the task to identify language-related brain areas in a group of neurologically healthy participants. Additionally, we performed an individual-level analysis to study replicability and variability of the group-level results at the level of individual participants. Furthermore, to identify a more preferable control condition for language localization, the active and passive control conditions were used for the group- and individual-level analyses. Moreover, we evaluated the applicability of the SC task for language lateralization assessment. Findlay et al. (2012) have demonstrated great correspondence between language lateralization assessed via MEG-based beta desynchronization and the classical intracarotid amobarbital procedure (Wada test). These results support the applicability of the method to indicate the language-dominant hemisphere (Findlay et al. 2012). Based on the available literature, language

lateralization was expected to correlate with hand dominance (Elin et al. 2022; Bolgina et al. 2016; Karpychev et al. 2022).

2 | Materials and Methods

2.1 | Participants

Twenty-two native Russian speakers took part in this study on a voluntary basis. The participants had normal (or corrected to normal) vision and no history of neurological diseases. Due to numerous noisy trials, data from one participant were dropped from the analysis. The final sample consisted of 21 participants aged between 18 and 37 years ($M_{age}=23.5$, $SD=5.36$, six males). Participants' handedness was assessed by the Russian adaptation of the Edinburgh Handedness Inventory (Oldfield 1971). Sixteen participants, whose scores ranged from 30 to 100, were considered right-handed; two participants with scores from -100 to -30 were left-handed; and three other participants were ambidextrous.

The study was approved by the HSE Committee on Interuniversity Surveys and Ethical Assessment of Empirical Research, and each participant signed an informed consent prior to the beginning of the experimental session.

2.2 | Stimuli

The design of the study included one experimental (SC) and two control conditions (no task and syllable repetition). The sentences used in the present study were taken from Elin et al. (2022), where the same task was implemented for the fMRI localizer. Every incomplete sentence consisted of three words of no longer than three syllables. Verbs in the sentences were put in the present or past tense and required a direct object. Details on the selection, structure, and linguistic parameters of the stimulus material are described elsewhere (Elin et al. 2022). The authors reported a high level of performance for this task, which might support the adequacy of the stimulus selection principles (Elin et al. 2022).

Stimuli for the active control condition (i.e., syllable repetition) consisted of one phonotactically acceptable Russian CV syllable (consonant and vowel) repeated three times. To match both conditions (i.e., SC and syllable repetition) on the number of

letters, each syllable was modified to have multiple repeated vowels. For example, a syllable *ло*—"lo" was used to create a pseudosentence *Лooooooo лoooo лooooooo...*—"Looooooo looooo loooooo..." The readers were instructed to produce a single short syllable with no need to extend the vowel utterance. We used the intertrial period, when a fixation cross was presented prior to the stimulus onset as the passive (no-task) control condition.

2.3 | Procedure

At the beginning of the experiment, there was a training session that consisted of three SC and active control trials, after which the participants had an opportunity to ask questions to clarify the task. The training session was not included in the final analysis. Subsequently, the main session started. Each trial started with the fixation cross presented for 1000 ms. Both SC and syllable repetition trials were presented in a randomized order in a word-by-word manner. Each word was displayed for 500 ms, followed by a blank screen for 300 ms. After the last (third) word, there was a 3000-ms-long pause, followed by the appearance of three dots for 2000 ms and a blank screen for an additional 1000 ms (Figure 1). The participants had to read words silently off the screen and complete the sentence out loud with a semantically relevant word in a correct word form when the three dots appeared. The task was virtually the same for the active control condition, except that the participants had to simply repeat the presented syllable. Fixation cross presentation from -500 to -200 ms (relative to the stimulus onset) was used as the passive control condition.

The main session was divided into four blocks of 30 sentences and 30 syllables each. The whole experimental procedure took 30 min on average.

2.4 | MRI Data Acquisition and Processing

High-resolution structural T1-weighted images were collected from each participant. Technical details of the scanners used for the data acquisition are provided in the Table S1.

The MRICroGL software (<https://www.nitrc.org/projects/mricrogl/>) was used to convert raw files from DICOM to NIFTI file format for the following processing. Structural T1-weighted



FIGURE 1 | Sentence completion and control paradigms. Note: Prestimulus interval (-500 to -200 ms) was used as a passive control condition. Active (syllable repetition) control condition aimed to control for non-linguistic processes.

MRI images were submitted to the FreeSurfer software in order to construct boundary-element models of grey matter using a watershed segmentation algorithm (<https://surfer.nmr.mgh.harvard.edu/>, FreeSurfer 4.3 software; Martinos Center for Biomedical Imaging, Charlestown, MA).

2.5 | MEG Data Acquisition and Preprocessing

MEG data were recorded in a magnetically shielded room (AK3b, Vacuumschmelze GmbH, Hanau, Germany) via a dc-SQUID Neuromag VectorView system (Elekta-Neuromag, Helsinki, Finland), containing 306 active channels: 204 planar gradiometers and 102 magnetometers. The raw data recording parameters were set up to a sampling frequency of 1000 Hz and the band-pass filtering between 0.003 and 330 Hz.

3Space Isotrak II System (Fastrak Polhemus, Colchester, VT, United States) was used for the participants' head shape digitalization. Nasion, right, and left preauricular points were used as anatomical landmarks in addition to randomly distributed points on the scalp (no less than 100 points per participant). Head movements were continuously monitored by four Head Position Indicator coils throughout the study.

Four electrodes recorded horizontal and vertical eye movements for further artefact removal. Two of them were located above and below the left eye, the others at the outer canthus of each eye. Additionally, two bipolar electrodes on the upper sternum and on the lower left ribs recorded electrocardiogram to remove cardiac artefacts from the recording.

The signal space separation (SSS; Taulu and Simola 2006) algorithm was used to remove the external noise in MEG channels via the MaxFilter software (Elekta Neuromag). Next, the recordings were downsampled from 1000 to 250 Hz. Subsequently, a high-pass filter of 1 Hz was applied to the data to eliminate slow drift in the signal. To remove cardiac and eye-movement artefacts from the data, an independent component analysis was performed via “fastica” method with 20 components implemented in the MNE library (Ablin et al. 2018; Gramfort et al. 2013).

Next steps of data analysis were performed using custom Python scripts based on the MNE library for the analysis of neurophysiological data (Ablin et al. 2018). Raw recordings were cut into epochs from −1000 to 6000 ms (hereinafter, time is indicated relative to the onset of the first word/syllable in a trial). The interval was chosen in order to include the interval of interest (−500 to 5100 ms) with additional time points for the time-frequency transformation. If within the interval of interest, the raw signal on any MEG channel surpassed the threshold of ± 3000 fT; the epoch was marked as “bad” and was discarded from the analysis.

The following steps were performed separately for the passive and for the active control comparisons. For the comparison against the passive (no-task) control condition, a standard mean baseline correction was applied. Specifically, beta power in the prestimulus interval (from −500 to −200 ms) was averaged and then subtracted from each time point of

each corresponding SC trial. For the active control condition, there was no direct correspondence between the SC and syllable repetition trials due to the randomized trial presentation procedure. In order to account for it, a slightly different procedure was implemented to correct for the active baseline condition. Because the lengths of the SC and syllable repetition trials were equal (i.e., from −500 to 5100 ms), the signal corresponding to the latter task was averaged across all trials and subtracted from the signal within each trial of the SC task. As a result, the average time course of beta power during the syllable repetition task was subtracted from each individual. This complementary baseline correction was used in order to eliminate noise from the data and to compare the SC and syllable repetition conditions in the study.

2.6 | MEG Source-Level Analysis

A separate single layer boundary element model (BEM) was created for each participant by the FreeSurfer watershed algorithm using an individual T1-weighted MRI scan. MEG data were co-registered to the structural MRI based on three fiducial points (the nasion, and the left and right preauricular points). Subsequently, the forward models were estimated for the surface source space (4098 sources per hemisphere). The baseline period (−500 to −200 ms) was used to estimate noise covariance matrices. To reconstruct cortical sources of power changes in the beta-frequency range (17–25 Hz), we used a standardized low-resolution brain electromagnetic tomography (sLORETA; Pascual-Marqui 2002) method with complex Morlet wavelet with 8 cycles. To compute source-level time courses of induced power modulations, estimated power was averaged within the beta-frequency range and baseline corrected according to the following formula: $(x - \text{mean}[\text{baseline}]) / \text{mean}[\text{baseline}]$, where x is the beta-power at each time point, baseline is the beta-power change computed over the baseline interval. For the group-level analysis, individual cortical maps were averaged across epochs and projected to the common anatomical space (FreeSurfer's fsaverage). Accordingly, individual participants' time courses of beta power were averaged across trials for the group-level analysis. Individual-level analysis, in its turn, was conducted at the level of trials.

Three time intervals of interest (TOI) were defined. Each interval (TOI1: 300–800 ms; TOI2: 1100–1600 ms; TOI3: 1900–3000 ms) corresponded to processing of the first, second, and third words of an experimental sentence with the pause that started after the last word to include word-selection process and to avoid motor preparation that appeared prior to response onset. For each TOI, we omitted the first 300 ms of stimuli processing in order to exclude activity associated with nonspecific visual processing. Regarding TOI3, source-level beta power was once again baseline corrected using mean baseline correction and averaged across each TOI.

2.7 | Statistical Analysis

The same statistical assumptions were used for the individual- and group-level analyses: Because we were interested in beta

desynchronization, the statistical testing was restricted to the negative difference from zero.

For the statistical analysis, the obtained cortical estimates of beta desynchronization were submitted to the spatio-temporal cluster test against zero. In the case of the passive control condition, the procedure would allow us to test whether the SC and the passive (no-task) control condition differ. For the active control condition, in its turn, the same procedure would allow us to test whether the SC and active control condition (i.e., syllable repetition task) differ. The permutation test was performed using a distribution of t -statistics for the SC and each control condition separately and every cortical vertex by 10,000 permutations (Monte Carlo estimate). The resulting statistics were considered significant when they surpassed the t -threshold (-2.53 for the group-level analysis; for the individual-level analysis, a threshold was derived for each participant from the number of artefact-free trials with $\alpha=0.01$), computed based on the number of participants and the primary threshold of 0.01 . The distribution of t -statistics represented the fraction of t -statistics larger than the given threshold, and $p=0.05$ was used as a threshold to select spatio-temporal clusters significantly different between the experimental and each control condition separately.

Anatomical labelling of resulting activation clusters was performed based on the Desikan-Killiany parcellation atlas (Desikan et al. 2006).

For the individual-level analysis (similar to Elin et al. 2022), we focused on the following language-related regions of interest (ROIs): pars triangularis and pars opercularis of the inferior frontal gyrus, caudal part of the middle frontal gyrus, precentral and postcentral gyri, supramarginal and inferior parietal gyrus, superior and middle temporal gyri. Left pars triangularis and pars opercularis are associated with numerous language processes, including speech production (Basilakos et al. 2018), interaction of semantic and syntactic information (Hagoort 2005), and conceptual and lexical word selection (Zyryanov et al. 2020). Middle frontal gyrus is implicated in language comprehension (Briggs et al. 2021). Precentral and postcentral gyri are essential for motor and sensory functions (Alahmadi 2024). Supramarginal and inferior frontal gyri are related to semantic processing and visual word recognition (Stoeckel et al. 2009; Turker et al. 2023). Superior temporal gyrus plays a role in language comprehension (Bhaya-Grossman and Chang 2022), while the middle temporal gyrus is considered a hub of syntactic comprehension (Yu et al. 2022). Additionally, we analyzed the regions of the strongest beta desynchronization found at the group-level analysis.

Moreover, the lateralization index (LI) was computed for each participant based on the estimate of significantly desynchronized vertices in each hemisphere. The following formula was implemented: $LI = (L - R) / (L + R)$, where L and R correspond to the sum of t -values of the significant clusters in the left and right hemispheres, respectively, computed by the one-sample spatio-temporal clustering test. To test for a significant relation between the handedness score and the LI, a correlation test was conducted between the results of the questionnaire and LI

computed for each analyzed time interval. To address the issue of multiple comparisons, FDR correction was applied to the obtained p -values.

3 | Results

3.1 | Passive Control Condition

3.1.1 | Group-Level Results for the Contrast With the Passive Control Condition

The SC task contrasted with no task (i.e., passive control condition) elicited statistically significant desynchronization during TOI3. Specifically, the spatio-temporal permutation t -test revealed two significant clusters. The first cluster ($p=0.022$; Figure 2A) included 182 vertices and covered the left paracentral and cingulate gyri. The second cluster of 920 vertices found within TOI3 ($p<0.001$; see Figure 2A) included the left precentral and postcentral gyri, parietal, temporal, and insula cortices, as well as pars opercularis and pars triangularis. No significant beta desynchronization was observed within TOI1 and TOI2 in comparison with the passive control condition. The MNI (Montreal Neurological Institute) coordinates of the peak beta desynchronization for each cluster are provided in Table 1.

3.1.2 | Individual-Level Results for the Contrast With the Passive Control Condition

Figure 2B mainly replicates the group-averaged patterns of significant beta desynchronization at the level of individual participants. The frequency of desynchronization in each ROI is represented in Table 2. In general, within TOI1, the angular gyrus was the most frequently engaged brain area among the ROIs, followed by the supramarginal gyrus, STG and MTG. TOI2 was associated with clusters of desynchronization that included the left postcentral gyrus in the majority of participants, the precentral gyrus, and the supramarginal and angular gyri. TOI3 elicited significant desynchronization in the same left-lateralized set of ROIs, followed by the pars triangularis of the inferior frontal gyrus. The detailed information about the frequency of activation of each brain region is provided in Table S2.

3.2 | Active Control Condition

3.2.1 | Group-Level Results for the Contrast with the Active Control Condition

The spatio-temporal cluster test identified clusters of significant beta desynchronization in all three TOIs for contrast of the SC with the syllable repetition task (see Figure 3A). Four clusters were found within TOI1 (Figure 3A), covering regions in both left and right hemispheres. The first two clusters covered 97 ($p=0.022$) vertices in the left lingual, lateral occipital, and fusiform gyri and 125 vertices ($p=0.012$) in the left parietal and temporal regions. The third cluster, in its turn, included 119 vertices ($p=0.012$) in the right temporal areas, lateral occipital,

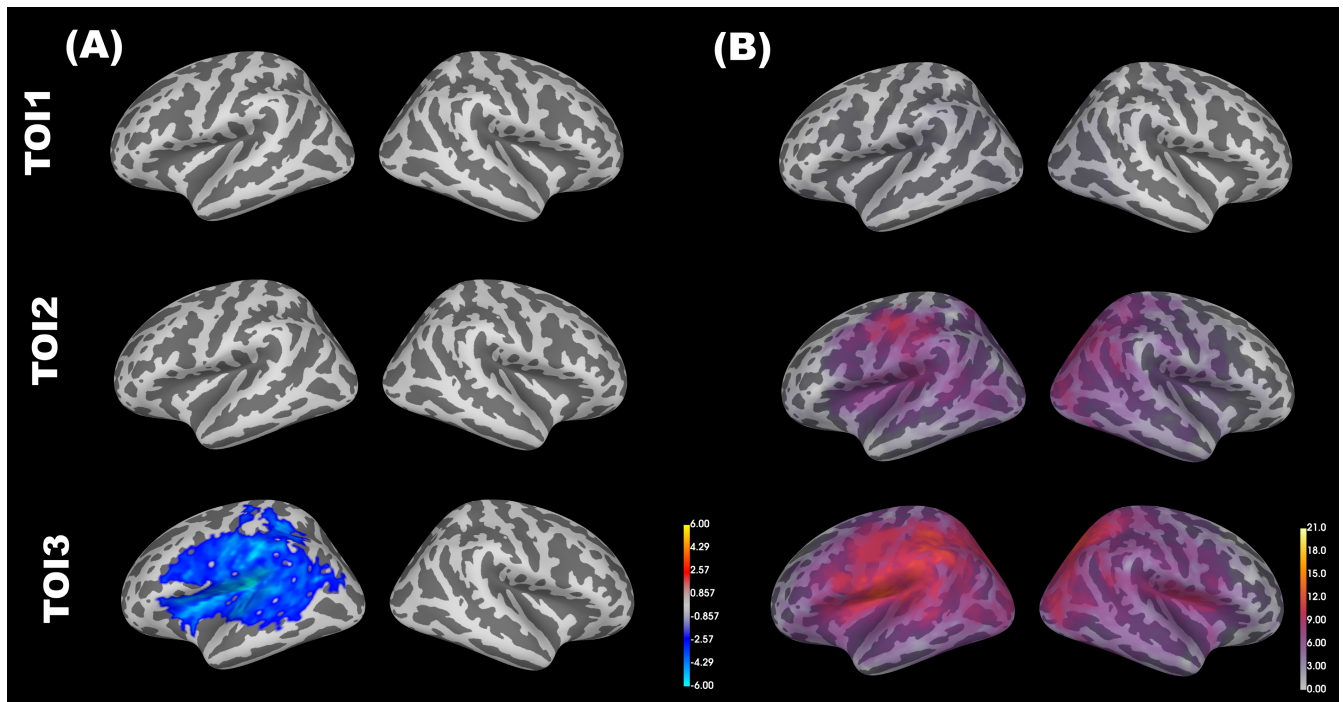


FIGURE 2 | Group- (A) and individual-level (B) results of the spatio-temporal cluster test in the source space for the TOI1, TOI2 and TOI3 in comparison to the passive control condition. *Note:* Only t -values of significant clusters are shown. The color saturation corresponds to the number of participants with significant beta desynchronization detected in the particular region.

TABLE 1 | Coordinates of peak beta desynchronization in the passive control condition.

TOI	Cluster	Cluster size	p	Peak MNI coordinates			t -value	Label (hemisphere)
				X	Y	Z		
3	1	182	0.022	-15	-30	37	-5.18	Posterior cingulate (L)
3	2	920	<0.001	-43	-26	22	-7.01	Supramarginal (L)

Note: The labels are provided based on the Desikan-Killiany atlas of cortical parcellation (Desikan et al. 2006).

TABLE 2 | Activation frequency in language-related ROIs at the individual level in the passive control condition.

ROI (hemisphere)	TOI1 (%)	TOI2 (%)	TOI3 (%)
Pars triangularis (L)	4.76	28.57	52.38
Pars opercularis (L)	4.76	33.33	52.38
Caudal MFG (L)	4.76	38.10	42.86
MTG (L)	9.52	38.10	42.86
STG (L)	9.52	38.10	57.14
Supramarginal gyrus (L)	9.52	52.38	76.19
Angular gyrus (L)	14.29	52.38	76.19
Precentral gyrus (L)	4.76	52.38	57.14
Postcentral gyrus (L)	4.76	57.14	71.43

and inferior parietal gyri. The last cluster covered 64 vertices ($p=0.04$) that included the right precuneus, lingual, and cingulate gyrus. TOI2 revealed two significant clusters (Figure 3A)

that covered cuneus, cingulate, and superior parietal areas in the left (124 vertices, $p=0.025$) and right (140 vertices, $p=0.021$) hemispheres. Within TOI3, the analysis revealed two clusters, the first of which covered parietal, insular, and temporal cortices, and precentral and postcentral gyri, pars triangularis, and pars orbitalis in the left hemisphere (Figure 3A) and included 1907 vertices ($p<0.001$). The second cluster of 293 vertices ($p=0.011$) was located in the posterior cingulate and precuneus regions of the right hemisphere. The MNI coordinates of the peak beta desynchronization found in each separate cluster are provided in Table 3.

3.2.2 | Individual-Level Results in the Active Control Condition

Intersubject patterns of activity resulting from the first-level analysis are presented in Figure 3B. Individual-level beta desynchronization within TOI1 of the SC versus the active control condition contrast was found in the left angular gyrus, followed by the supramarginal gyrus, STG, and MTG. Significant clusters of beta desynchronization also included precentral- and postcentral gyri. In addition to the previously

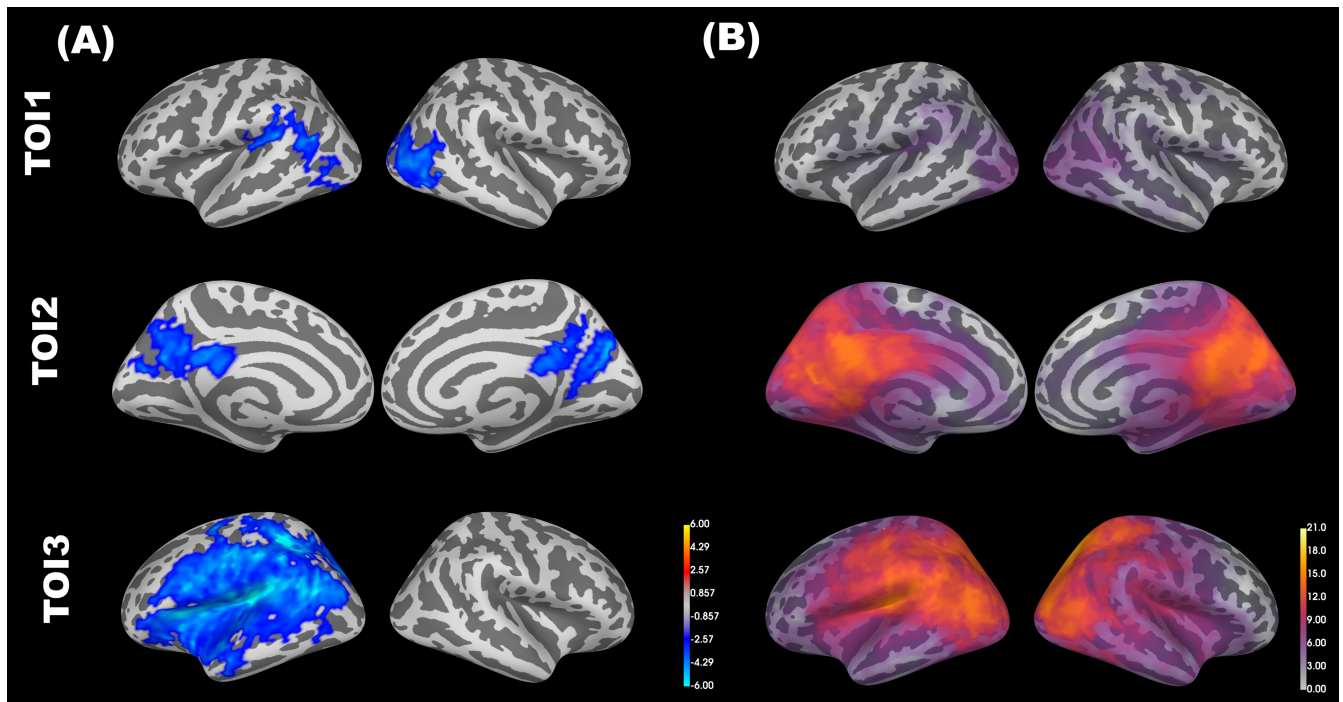


FIGURE 3 | Group- (A) and Individual-level (B) results of the spatio-temporal cluster test in the source space for the TOI1, TOI2 and TOI3 in comparison to the active control condition. *Note:* Only t -values of significant clusters are shown. The color saturation corresponds to the number of participants with significant beta desynchronization detected in the particular region.

TABLE 3 | Coordinates of peak beta desynchronization at the group level.

TOI	Cluster	Cluster size	p	Peak MNI coordinates			t -value	Label (hemisphere)
				X	Y	Z		
1	1	97	0.022	-24	-56	1	-3.96	Lingual (L)
	2	125	0.012	-38	-57	17	-5.26	Inferior parietal (L)
	3	119	0.012	45	-63	-6	-5.01	Inferior temporal (R)
	4	64	0.041	10	-64	26	-3.80	Precuneus (R)
2	1	124	0.025	-12	-63	24	-4.72	Precuneus (L)
	2	140	0.021	20	-71	28	-5.15	Precuneus (R)
3	1	1907	<0.001	-14	-26	36	-7.96	Posterior cingulate (L)
	2	293	0.011	7	-47	22	-5.14	Isthmus of cingulate gyrus (R)

Note: The labels are provided based on the Desikan-Killiany atlas of cortical parcellation (Desikan et al. 2006).

mentioned brain areas, TOI2 was associated with pars triangularis and the middle frontal gyrus (see Table 4). Following that, TOI3 engaged supramarginal and angular gyri most often, followed by the temporal ROIs and precentral and post-central gyri.

3.3 | LI

A correlation test was performed to examine the relation between the participants' handedness scores and LI. Because we did not find significant clusters for the TOI1 in the passive control condition, it was excluded from the LI analysis. The distribution of the activated vertices was normal in each TOI of both control conditions, except for the TOI1 ($W=0.774$,

$p=0.049$) and TOI2 ($W=0.897$, $p=0.043$) in the passive control condition. However, handedness scores diverged from the normal distribution ($W=0.716$, $p<0.001$). For this reason, the correlation was assessed using Spearman's rank correlation coefficient.

No significant correlation between handedness and lateralization indices was detected after the correction for multiple comparisons (see Table 5).

4 | Discussion

The current work was aimed at adapting the SC task (previously described and validated by Elin et al. 2022) for MEG

TABLE 4 | Frequency of activation of language-related ROIs in the active control condition.

ROI (hemisphere)	TOI1 (%)	TOI2 (%)	TOI3 (%)
Pars triangularis (L)	9.52	28.57	52.38
Pars opercularis (L)	9.52	38.1	47.62
Caudal MFG (L)	4.76	42.86	52.38
MTG (L)	19.05	52.38	66.67
STG (L)	19.05	52.38	71.43
Supramarginal gyrus (L)	28.57	66.67	80.95
Angular gyrus (L)	47.62	80.95	80.95
Precentral gyrus (L)	14.29	66.67	66.67
Postcentral gyrus (L)	14.29	66.67	66.67

TABLE 5 | The results of the Spearman correlation test between the handedness and lateralization index.

Condition	TOI	ρ	p	p (FDR-corr.)
Passive	1	0.112	0.858	0.857
	2	0.128	0.602	0.857
	3	0.045	0.850	0.857
Active	1	0.146	0.619	0.857
	2	0.152	0.546	0.857
	3	0.179	0.436	0.857

language localization and lateralization via assessing beta desynchronization. We used the original fMRI paradigm and implemented syllable repetition as an active control condition for the experimental SC. As expected, neurologically healthy participants had prominent clusters with beta desynchronization in the language-related areas of the brain. Furthermore, these clusters primarily emerged in the left hemisphere. Consistent with this, we did not observe a significant correlation between handedness and LI.

The original goal of the research was to confirm the general ability of the SC task and the beta desynchronization analysis to map language and to explore the potential of this paradigm for individual language localization and lateralization. Thus, we additionally investigated the replicability of the desynchronization pattern individually. In the SC versus the passive control condition, the participants' responses to incomplete sentences were compared with the absence of any stimuli during the intertrial period. Although no clusters were found during the first and second words processing (corresponding to TOI1 and TOI2, respectively) at the group level, some individual participants demonstrated desynchronization of the posterior language-related areas. Particularly, the supramarginal, angular, precentral- and postcentral gyri were activated in more than half of participants within TOI2, supplemented by activation of the STG and MTG in approximately a third of participants. These left parietal areas, including the

supramarginal and angular gyri, are often associated with semantic processing (Turker et al. 2023) and reading (Stoeckel et al. 2009). Given that the study required the participants to read sentences off the screen, the activation of these regions was expected.

Subsequent statistical analyses within the third word processing interval (corresponding to TOI3, respectively) revealed clusters of beta desynchronization in the left supramarginal and cingulate gyri when compared with the passive (no-task) control condition. Engagement of the left supramarginal gyrus may indicate enhanced integration of syntactic and semantic input (Turker et al. 2023). Moreover, individual-level beta desynchronization spread more anteriorly to the precentral, postcentral, middle, and inferior frontal gyri. Synergetic modulation of these brain areas could be involved in motor preparation and prediction of sensory feedback from the upcoming movement (Turker et al. 2023; Gale et al. 2021). Because our task involved not only motor preparation but also explicit verbal response, the engagement of the sensorimotor cortex at late stages is in line with these findings (Gale et al. 2021).

Noticeably, individual- and group-level analyses showed that the left pars triangularis was specifically activated during the third word in the SC versus the passive control condition. As pars triangularis is argued to be a hub of word selection and speech production, it plays a role in the interaction of semantic and syntactic information, language production, and conceptual and lexical word selection (Basilakos et al. 2018; Hagoort 2005; Lazar and Mohr 2011). Particularly, a stimulation study (Ishkhanyan et al. 2020) demonstrated that the left inferior frontal gyrus is implicated in the planning and production of a context-based grammatically valid response, which is relevant in the context of the SC task.

Moreover, more than half of the participants showed desynchronization in the left superior temporal cortex as compared with the passive control condition. Because the superior temporal gyrus is essential for both spoken and written language comprehension (Simos et al. 2000), its active engagement within the SC task could serve as an indicator of semantic processing.

For syllable repetition (i.e., the active control condition), we compared the same beta desynchronization response during the SC task with the beta desynchronization induced by repetition of syllables. The first word was characterized by the extended clusters of beta desynchronization in the occipital cortex bilaterally. In other words, the perception of real words was more demanding than the visual processing of syllables. Furthermore, reading the first word elicited more enhanced activation in the posterior part of the left fusiform gyrus, encompassing the visual word form area (Caffarra et al. 2021). It is a key brain structure that is causally engaged in orthographic processing (Sabsevitz et al. 2020; Turkeltaub et al. 2014). The higher activation of the area in response to words as compared with syllables observed in the current study further supports the visual specificity of this area for reading. Apart from the visual areas, noticeable activation was found in the left supramarginal gyrus. Overall, while the contrast with passive viewing did not reveal any patterns of beta desynchronization during the first word, the syllable repetition task highlighted desynchronization in the middle occipital,

temporal, and inferior parietal cortices associated with word recognition and reading in general (Castles et al. 2018; Cohen et al. 2003).

Subsequently, the second word was associated with more anterior clusters focused in the occipital cortex bilaterally. At the same time, stronger desynchronization for sentences as compared with syllables was evident in the bilateral cingulate gyri. According to a recent meta-analysis (Turker et al. 2023), bilateral cingulate gyri are domain-general regions consistently engaged in various cognitive tasks and, in particular, in semantic processing (Kuhnke et al. 2021). Thus, the significant activation of both left and right cingular areas when contrasting SC with syllable repetition could reflect more demanding semantic processing in SC as compared with the syllable repetition.

Two clusters of desynchronization for the third word relative to syllable repetition included bilateral paracentral areas and cingulate gyri, the left precentral and postcentral gyri, middle and inferior frontal gyri, supramarginal gyri, and angular gyri. The observed pattern of desynchronization might be an indicator of semantic processing and articulatory preparation processes observed within the same interval for the syllable repetition task.

Interestingly, at the individual level, during the first and second words, reading and repeating syllables highlighted the clusters in the temporal, parietal, and occipital cortices of the right hemisphere, such as the inferior parietal gyri and cuneus. Presumably, the syllable repetition task highlighted the attentional efforts required to perform the SC task.

In general, both active and passive control conditions allowed us to detect brain regions conventionally associated with various aspects of language processing. However, the results obtained for the syllable repetition engaged the areas more consistently among the participants as compared with the passive (no-task) control condition. This could reflect higher reliability in locating language-specific brain regions.

Nevertheless, further research on participants with brain damage and comparison with the traditionally implemented fMRI paradigm and Wada test is required to explore the applicability of the MEG paradigm for presurgical language localization. Despite the wide use of the former, it has been shown that the neurovascular coupling that is the critical assumption of the fMRI signal may be disrupted due to even minor dysfunctions (Agarwal et al. 2016). Thus, fMRI as a tool for language mapping may be potentially less applicable to some people with cerebrovascular disorders. MEG, in its turn, does not rely on the blood flow, because it measures the magnetic activity of neuronal pools directly. This feature makes MEG-based results potentially more reliable and resistant to changes in brain function. Nevertheless, our results are in line with the previous fMRI research on a healthy control group, indicating the applicability of the paradigm for language mapping (Elin et al. 2022).

Finally, in order to explore the ability of the task to detect the language-dominant hemisphere, we assessed the relation between language lateralization and handedness. Based on the previous research with the same task, the higher “right-handedness” score was expected to be associated with more

left-lateralized language dominance (Findlay et al. 2012; Bolgina et al. 2016). However, the hypothesis was not supported, because the analysis did not reveal a significant correlation between the parameters. The nonsignificant association found in the current study could be related to the inclusion of left-handed and ambidextrous participants, who generally demonstrate less coherent patterns of language dominance (Packheiser et al. 2020) or insufficient sample size to detect the effect. At the same time, substantial studies indicate negligible (if any) association between handedness and language lateralization that barely reaches 40% (Packheiser et al. 2020; Somers et al. 2015). Apart from that, the inconsistency between the results could be due to the differences in the implemented tasks, variability of the indices, and approaches used to determine lateralization (Vingerhoets et al. 2023). Bradshaw et al. (2017) demonstrated how the methods and paradigms used to measure language laterality could result in LI variability, thus limiting the ability to compare the outcomes of different studies. A standardized approach to assess lateralization could increase the possibility of comparing the results of different studies (Vingerhoets et al. 2023). Thus, the available evidence points to the need for caution in estimating language lateralization based on hand dominance, because the latter only marginally relates to the former.

This study has several limitations. Firstly, although we performed both individual and group analyses, the group-level results should be interpreted with caution. Because these data were aggregated over a group of participants and warped to the average MNI template, the spatial precision of the activity peak may be limited.

Secondly, while we recorded data from the participants irrespective of their reported handedness, the distribution of people with less typical hand dominance (i.e., left-handed and ambidextrous) was not equal. Strong variation in group sizes could account for the absence of association between hand dominance and language lateralization. Future studies would benefit from equalizing the groups by number of participants. In general, expanding a healthy control group could promote reliability and generalizability of the results.

Moreover, it is important to note that the two control conditions (i.e., no task and syllable repetition task) had different characteristics, such as task complexity and trial duration. While the no-task control condition was a baseline period of the same trial, the syllable repetition task was a separate task. While the passive control condition is a more conventional option, the use of the active control condition could be more preferable for the purposes of language mapping.

Additionally, based on the previous studies, we have specifically focused on the analysis of beta-frequency oscillatory components, while other frequency bands could play equally important roles in language processing. Furthermore, extensive exploration of the interaction between various frequency bands via phase-amplitude coupling could describe more complex processes that underlie language processing in the brain.

The aim of the study was to adapt the SC task to MEG noninvasive language mapping and to test the procedure in a neurologically healthy control group. To control for the linguistic

input, active (syllable repetition) and passive (no-task) control conditions were implemented. The task successfully activated both anterior and posterior language areas as a function of time, with more distributed and pronounced desynchronization appearing during the processing of the last word prior to the verbal response. In line with clinical case studies, the current research did not find a significant correlation between language lateralization (measured by semantic and morphosyntactic processing) and the participants' handedness, indicating left-hemispheric language dominance. Despite noticeable individual variability in the activated brain areas, the overall ability of the method to capture beta desynchronization in the language-related regions can serve as a starting point for further clinical research and application of the method in individual presurgical mapping.

Author Contributions

Mariya Protopova: investigation, formal analysis, writing – original draft, writing – review and editing. **Tatiana Bolgina:** investigation, data curation, formal analysis, writing – review and editing. **Vardan Arutiunian:** methodology, writing – review and editing. **Olga Dragoy:** investigation, writing – review and editing, resources, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available upon request by emailing the corresponding author.

Peer Review

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ejn.70282>.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Parameters of the MR scanners used to obtain anatomical T1-weighted images of the participants. **Table S2:** Frequency of activation of Each brain region within each experimental condition.