

**Investigating Beta Oscillation Dynamics During Rhythmic Auditory Processing in
Stuttering**

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Author Note

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Abstract

Stuttering is a neurodevelopmental speech disorder characterized by involuntary disruptions in speech fluency and has been associated with atypical neural processing of speech timing and rhythm. Prior research suggests that individuals who stutter may exhibit atypical neural processing of rhythmic auditory input, particularly in timing-related processes. In typical fluent listeners, beta-band (15 - 25 Hz) activity shows systematic modulation during rhythmic auditory stimulation, reflecting a mechanism related to the temporal prediction. In this study, we examined beta modulation during rhythmic processing in adults and children who stutter (AWS, CWS), compared to age-matched controls (ANS, CNS). We hypothesized that individuals who stutter would show altered beta modulation relative to controls, due to prior evidence suggesting that stuttering is associated with differences in the timing and coordination of neural oscillations involved in speech and auditory processing. EEG data were acquired during passive listening to isochronous piano tones (500 ms inter-tone interval; 2 Hz) to assess beta-band oscillatory activity in 15 ANS and 22 AWS (ages 19.5–51.75 years), and in 8 CNS and 6 CWS (ages 7.16–13.66 years). Time–frequency and spectral analyses were used to quantify beta power and phase at the 2 Hz stimulus rate. Analyses revealed comparable temporal beta activity and phase angle oscillatory activity at 2 Hz, with no consistent group differences between participants who stutter and controls in either adults or children. A right-hemisphere phase difference between adults and children who stutter suggests differences in the timing rather than the amplitude of beta oscillations. Collectively, these results provide insight into how neural timing mechanisms may operate across development in individuals who stutter.

Acknowledgements

I would like to thank my Principal Investigator, Dr. Soo-Eun Chang, for her support throughout my time in the Speech Neurophysiology Lab and the guidance she has provided in the writing of this thesis. I am deeply grateful to have her as a mentor and to have learned so much from her, as she has greatly contributed to my growing knowledge of neurodevelopmental stuttering.

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Investigating Beta Oscillation Dynamics During Rhythmic Auditory Processing in Stuttering

Background

Stuttering is a multifactorial, variable speech disorder that affects approximately 5-8% of children and 1% of adults (Månsson, 2000; Reilly et al., 2009). The proportion of adults affected by stuttering is notably lower than that of children, because most children recover over time without intervention. Stuttering has been associated with atypical neural activity related to timing and rhythm processing, including alterations in beta-band oscillations (Etchell et al., 2016; Korzeczek et al., 2022; Mersov et al., 2016).

Stuttering involves disruptions in rhythmic timing that can manifest in several ways. In this context, rhythm refers to the organization perceived from temporal predictions of physical sound patterns (McAuley & Jones, 2003). Chang and Guenther (2020) described distinctions between types of stuttering (i.e., disfluencies) related to the Cortico-Basal Ganglia-Thalamocortical loop (CBGTC), which plays a critical role in speech motor planning, movement timing, and the initiation of fluent speech. Disruptions within this neural timing system may manifest as distinct types of disfluencies during speech production, including prolongations, blocks, and other phenomena. Prolongations occur when the termination time for the current phoneme is not recognized, whereas blocks occur when the initiation time for the next phoneme is not appropriately triggered (Chang & Guenther, 2020).

These speech disruptions may be related to differences in rhythmic timing and neural oscillatory activity. Deficits in rhythm perception and altered beta-band timing mechanisms have been reported in individuals who stutter (Chang et al., 2016; Korzeczek et al., 2022; Mersov et al., 2016; Wieland et al., 2015). Specifically, individuals who stutter may experience greater

difficulty predicting the timing of phonemes when speaking, which can disrupt rhythmic conditions. Neural regions within the CTBTC loop are involved in internal rhythm monitoring and timing processes that are supported by neural oscillatory activity, including beta-band dynamics.

Temporal Predictions and Neural Oscillation

Examining the brain regions implicated in stuttering, as well as the functional characteristics and connectivity of speech-related neural networks, helps clarify the neural mechanisms that may contribute to the disorder. Disruptions in internal timing, motor planning, and auditory–motor integration within CBTC circuits have been associated with reduced speech fluency and the emergence of disfluencies such as prolongations and blocks. Speech processing is also characterized by hemispheric specialization. Lateralization refers to the tendency for specific cognitive functions to be preferentially supported by one hemisphere of the brain; for instance, language production and processing are typically left-lateralized (Morillon et al., 2010). Several methods can be used to confirm left-lateralized speech production in the brain, and this paper will focus on electroencephalogram (EEG) data.

Left lateralization is characterized by increased neuronal activity in left-hemispheric regions related to speech and language (Chang & Guenther, 2020). EEG can detect neuronal activity by measuring oscillatory signals that reflect synchronized firing of neuronal populations. In the context of speech and auditory processing, beta oscillations have been implicated in the integration of somatosensory and motor information (add some reference). More broadly, beta oscillations are thought to support interactions between auditory and sensorimotor cortices that contribute to temporal

predictions. Temporal prediction allows the sensorimotor cortex to anticipate upcoming auditory events and modulate beta oscillations accordingly. Beta oscillatory activity can therefore be measured using EEG to assess the strength of activation during various cognitive tasks, such as listening to isochronic tones.

Morillon et al. (2010) conducted a study that measured participants' brain activity using EEG and blood-oxygen-level-dependent signals as participants passively listened to rhythmic sounds. In the study, asymmetry was detected in the left somatosensory and inferior parietal regions, with greater intrinsic activity compared to homologous right-hemisphere regions. These findings suggest that left-hemispheric regions play an important role in auditory and motor processing related to rhythmic perception. Additional work has shown that lateralization in auditory and somatosensory regions can be predicted by lateralization in motor areas at syllabic rates, even during passive listening while watching a silent film (Schroeder, 2010). Together, these findings suggest that left-hemisphere activity may contribute to effective auditory prediction, whereas atypical lateralization may be associated with altered rhythmic processing

The processing of auditory stimuli in the brain involves auditory-motor coupling, or interactions between auditory perception and motor-related neural systems. Beta oscillations have been shown to facilitate coordination between the auditory and sensorimotor cortices (Fujioka et al., 2012). During tasks involving isochronous tones and motor response (typical in many studies), increased beta activity has been observed in both auditory cortex and sensorimotor areas (Fujioka et al., 2012). In addition, motor regions may support auditory processing by providing predictive timing cues through interactions with lower-frequency oscillations, such as delta and theta rhythms (Arnal, 2009; Luo, 2010).

Rhythmic Entrainment in Auditory Processing

Rhythmic entrainment refers to the alignment of neural oscillatory activity with the temporal structure of auditory stimuli. Studies of speech production and processing have shown that beta oscillations are modulated when temporal predictions are guided by sensory input (Arnal et al., 2015; Arnal & Giraud, 2012). The present study focused on rhythmic processing and discrimination of isochronous tones rather than speech production. Rhythmic auditory processing is associated with beta oscillatory activity, as appropriate modulation of beta oscillations appears to support accurate temporal prediction.

Arnal et al. (2015) employed a delayed-target detection task and reported that participants with better performance showed increased prestimulus beta activity and optimal engagement of low-frequency delta oscillations. These findings suggest that beta oscillations contribute to the timing of sensory predictions. Prior work has reported atypical beta activity before and after response in individuals who stutter, which may reflect differences in sensorimotor integration (Caruso et al., 2022). For example, children who speak fluently show typical beta activity in the left hemisphere, whereas those who stutter show weaker beta modulation across both hemispheres (Caruso et al., 2022). Reduced beta modulation may be associated with less precise temporal prediction of sensory events, which could contribute to disruptions in rhythmic coordination.

Differences in neural structure and connectivity may further influence beta modulation and temporal prediction. Caruso et al. (2022) used a non-speech motor task to measure reaction time and neural oscillatory activity, and reported associations between sensorimotor dysfunction and altered neural oscillations in children who stutter. While multiple frequency bands contribute to speech and motor control, the present study focuses on beta oscillations due to their proposed role in timing and prediction, and their strong association with stuttering. Previous work has

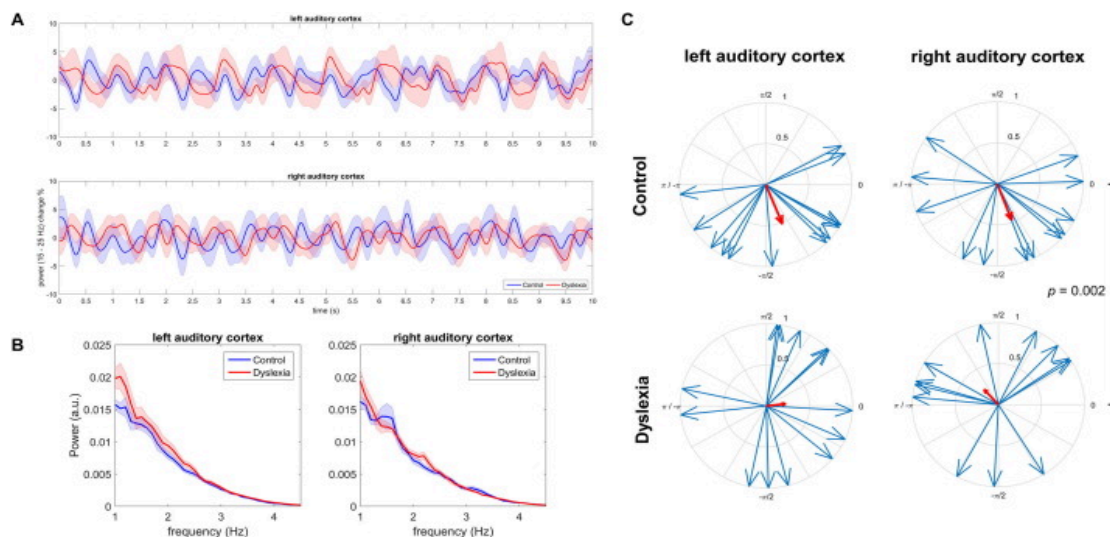
reported slower reaction times in individuals who stutter, which has been associated with differences in beta modulation and hemispheric lateralization (Jenson, 2018; Mersov, 2016; Rastatter, 1998; Salmelin, 2000; Sengupta, 2017, 2019; Sowman, 2012). Reduced left-lateralization and altered interhemispheric connectivity have also been reported in children who stutter, suggesting differences in the neural organization supporting timing and rhythm.

Guiding Studies

This paper draws on the work of Chang et al. (2021). In their study, electroencephalographic (EEG) activity was measured in 13 adults with developmental dyslexia and 13 matched controls as part of a larger research project. Time-frequency neural activities generated from the left and right auditory cortices were analyzed, and beta power fluctuations at a 2 Hz stimulus presentation rate were compared between the dyslexia and control groups (Chang et al., 2021). The phase of beta power fluctuation appeared to differ between individuals with dyslexia and the controls, with opposite phase patterns observed at that stimulus rate, which could reflect differences in auditory rhythm perception and tracking in dyslexia.

Figure 1.

Beta activity/fluctuations/power and phase angle results from the Chang et al. study (2021)



Note. Figure A shows typical beta activity in the control group (blue) and atypical beta activity in the dyslexia group (red). The control group demonstrated a peak in fluctuations (anticipatory beta increase) at the time of tone onset and troughs between tones. The dyslexia group showed a peak in fluctuations between tones and troughs at the time of tone onset. Figure B showed no significant difference in beta fluctuations between the two groups, and subsequent testing was performed. The phase angle results in Figure C suggest significant group differences in the right auditory cortex at 2 Hz (stimulus tone presentation), indicating an opposite phase of beta power fluctuations. This image was adapted from Chang et al. (2021).

Current Study

This thesis builds on prior work examining the neural oscillatory mechanism underlying rhythmic auditory processing. Using methodologies similar to those described in the guiding studies, the present study examined whether beta oscillatory modulation during isochronous tone listening differs between individuals who stutter and those who do not.

By examining beta oscillatory dynamics associated with rhythmic entrainment to isochronous auditory stimuli, this research aims to advance understanding of the neural mechanisms underlying rhythm processing in individuals who stutter. While Chang et al. (2021) previously tested these variables in individuals with dyslexia, the current study focuses on individuals who stutter, including both adults and children. Specifically, the study examined how beta-band activity is internally synchronized with isochronous tones.

We anticipated that beta oscillatory activity in those who stutter would differ from that in controls at the 2 Hz stimulus rate in both adult and child participants, reflecting potential differences in beta modulation during rhythmic auditory processing.

Materials and Methods

Participants

This study consisted of 37 adult participants, including 22 adults who stutter (AWS) and 15 adults who do not stutter (ANS), and 14 child participants, including 6 children who stutter (CWS) and 8 children who do not stutter (CNS). The adult participants ranged from 19.5 to 51.75 years of age ($M_{\text{age}} = 27.85$, $SD_{\text{age}} = 11.18$, 72% females, 28% males), and the child participants ranged from 7.16 to 13.66 ($M_{\text{age}} = 9.71$, $SD_{\text{age}} = 1.87$, 21% females, 79% males) years of age. All participants were monolingual English speakers who performed within normal limits on standardized measures of language and cognitive performance. All study procedures were approved by the Institutional Review Board (IRB) of the University of Michigan - Ann Arbor and the University of Pittsburgh. The procedures, experimental setup, and equipment were identical at both these institutions. Participants were recruited from the Midwest, United States, through a combination of flyers, email outreach, and online postings shared with the local community. After a full explanation of the study, informed consent to participate was obtained from all adult participants in written form and from all child participants in verbal or written form, depending on age, and parents in written form in accordance with the Declaration of Helsinki. Participants were compensated for their time during interviews and psychophysiological assessments.

To participate in this study, subjects must meet specific criteria to limit confounding variables. To be eligible for the study, participants needed to (1) pass a hearing test that measured frequencies of 1k, 2k, and 4k Hz at a threshold of 25 dB (ASHA Panel on Audiologic Assessment, 1997), (2) have a nonverbal IQ score within normal ranges (Ritter et al., 2011), (3) not take any medications that could interfere with nervous system functioning, and (4) not have any past medical history that includes injury to the central nervous system (head/neck regions).

Participants who stuttered were diagnosed by a licensed American Speech-Language and Hearing Association-certified speech-language pathologist, and control subjects had no history of stuttering or other speech and language disorders in their families. Stuttering behavior and severity were evaluated in accordance with the Stuttering Severity Instrument (SSI-4; Riley 2009). The study took place at the Speech Neurophysiology Lab at the University of Michigan Medicine Department of Psychiatry.

The demographics and behavioral scores of participants included in our final analyses are shown in Tables 1 and 2. Groups were matched on age, education, and cognitive ability. The groups did not differ significantly on the measures of age, IQ (TONI-4 and WASI-II), and years of education (child years of education were based on maternal educational attainment). In other words, there is no evidence of systematic group differences (all $p > 0.05$).

Table 1

Participant Demographics and Behavioral Performance among AWS and ANS

Measures	AWS	ANS	Range	Group Difference
No. Participants (F: M)	7:15	9:6		
Age (yr)	30.50 ± 12.67	24.69 ± 7.90	18 - 58.33	$t(34.80) = 1.72$, $p = 0.095$
TONI-4 Index Score	98.75 ± 7.67	105.43 ± 12.29	87 - 125	$t(21.42) = -1.87$, $p = 0.075$
TONI-4 Percentile	46.88 ± 18.81	60.29 ± 26.21	19 - 95	
SSI-4 Rater 1	22.26 ± 11.07		6 - 45	
SSI-4 Score	Very Mild: 8, Mild: 1, Moderate: 7, Severe:			

	1, Very Severe: 2			
Handedness	Right Handed: 14, Left Handed: 4, Ambidextrous: 1	Right Handed: 6, Left Handed: 1, Ambidextrous: 1		
Years of Education	14.39 ± 1.79	15.25 ± 2.49	12 - 18	$t(23.65) = -1.15,$ $p = 0.262$

Note. Demographic and behavioral information were typically obtained at the first longitudinal study visit or when the first high-quality fMRI scan was acquired for that participant. Group differences between adults who do (AWS) and do not stutter (ANS) were calculated by independent sample *t* tests and Welch tests for samples of unequal variances. Composite intelligence quotients (IQ) scores were based on performance on the Test of Nonverbal Intelligence-4 (TONI-4), a standardized assessment that measures abstract reasoning and problem-solving in individuals aged 6 to 89 (Brown et al., 2010). This test is ideal for individuals with language differences, as it uses simple gestures and avoids complex language and cultural bias. The composite stuttering severity rating was based on the Stuttering Severity Instrument-Fourth Edition (SSI-4; Riley, 2009) and calculated from the frequency, duration, and physical concomitants of stuttering moments during speech sampling. This standardized assessment is used by Speech-Language Pathologists, and the scale in the table above ranges from 1, meaning *very mild*, to 5, meaning *very severe*.

Table 2

Participant Demographics and Behavioral Performance among CWS and CNS

Measures	CWS	CNS	Range	Group Difference
No. Participants (F: M)	2:4	1:7		
Age (yr)	9.46 ± 2.35	9.91 ± 1.56	7.17 -	$t(8.21) = -0.41,$

			13.67	$p = 0.695$
TONI-4 Index Score	111.83 $\pm$ 12.12	108.88 $\pm$ 12.15	88 - 131	$t(10.94) = 0.45$, $p = 0.661$
TONI-4 Percentile	73.5 $\pm$ 25.19	62 $\pm$ 19.62	21 - 95	
WASI-II Verbal Score	122 $\pm$ 14.56	114.13 $\pm$ 8.1	99 - 140	$t(7.31) = 1.19$, $p = 0.270$
WASI-II Verbal Percentile	85.77 $\pm$ 19.88	79.88 $\pm$ 15.61	47 - 99.6	
SSI-4 Rater 1	17.67 $\pm$ 5.72		7 - 23	
SSI-4 Score	Very Mild: 1, Mild: 3, Moderate: 2, Severe: 0, Very Severe: 0			
Handedness	Right Handed: 6, Left Handed: 0, Ambidextrous: 0	Right Handed: 5, Left Handed: 0, Ambidextrous: 3		
Years of Maternal Education	16.83 $\pm$ 2.04	17.5 $\pm$ 0.93	13 - 18	$t(6.57) = -0.75$, $p = 0.480$

Note. Demographic and behavioral information were typically obtained at the first longitudinal study visit or when the first high-quality fMRI scan was acquired for that participant. Group differences between children who do (CWS) and do not stutter (CNS) were calculated by independent sample t tests and Welch tests for samples of unequal variances. Composite intelligence quotients (IQ) scores were based on performance on the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler, 2011) or the Test of Nonverbal Intelligence-4 (TONI-4; Brown et al., 2010). WASI-II provides index scores for verbal comprehension and perceptual reasoning, including a Full Scale IQ score for individuals aged 6 to 90 years and 11 months. The composite stuttering severity rating was based on the Stuttering

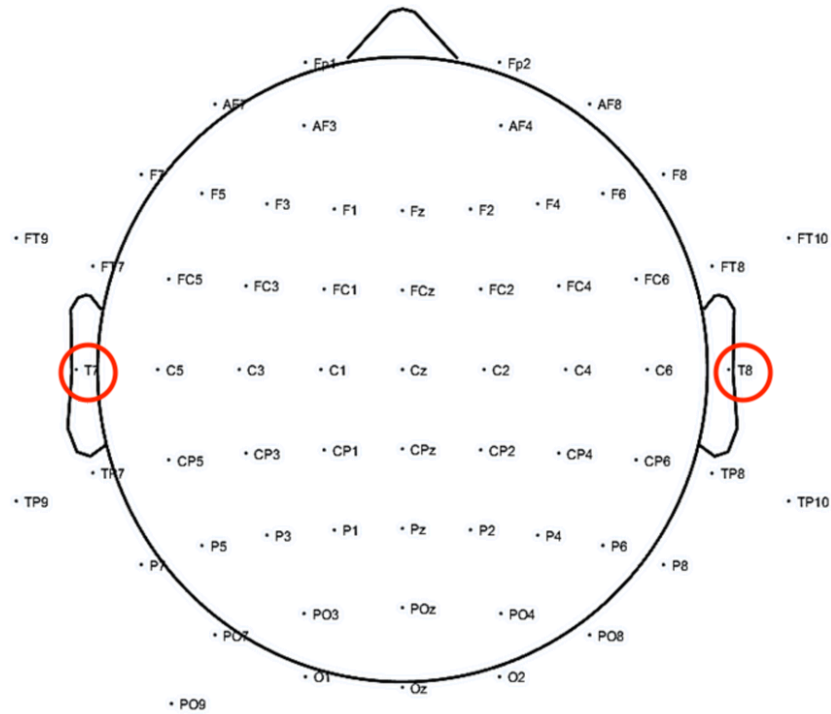
Severity Instrument-Fourth Edition (SSI-4; Riley, 2009) and calculated from the frequency, duration, and physical concomitants of stuttering moments during speech sampling. This standardized assessment is used by Speech-Language Pathologists, and the scale in the table above ranges from 1, meaning *very mild*, to 5, meaning *very severe*. The average years of education were measured by parents' (mothers') educational attainment.

Procedure

The entire study was conducted in a testing room with a controlled environment, where participants sat in an armchair while EEG data were recorded from the EEG cap (Figure 2). Each participant listened to a 5-minute isochronous tone sequence while watching a silent film titled *Wings* (Wellman & d'Arrast, 1929). Participants wore earbuds (Etymotic ER3C) to listen to the isochronous tones (at 68 dB SPL) and pay attention to the screen during the listening tasks. The tones used in this study were identical to those in the Chang et al. (2021) study, which included the C4 tone (262 Hz) presented for five minutes in total. The sequence used for this task comprises approximately 600 tones, each lasting 200 ms.

Figure 2.

Brain Vision Electrode Visualization of EEG Cap

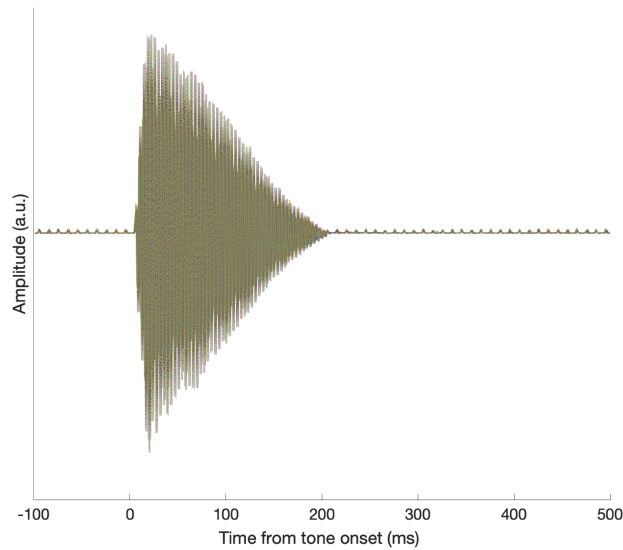


Note. EEG setup and channel locations for a participant. Electrode montage: The T7 and T8 electrodes measure the left (T7) and right (T8) auditory cortices. This image was adapted from Serrano et al. (2018).

EEG Data Recording and Processing

Figure 3a.

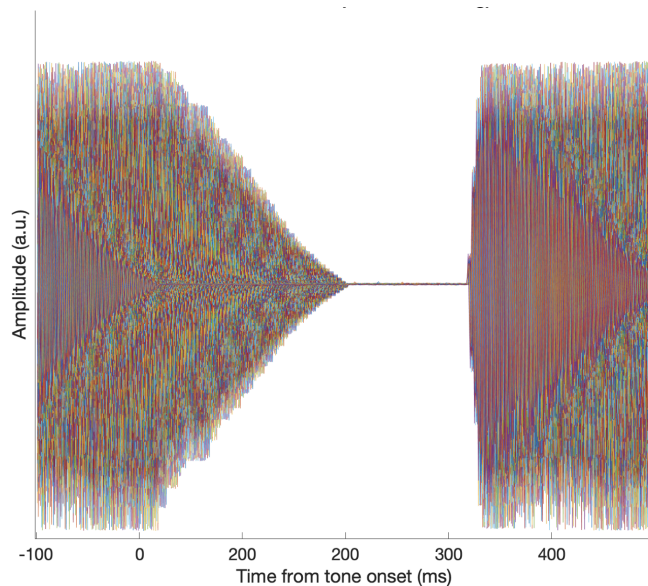
Stimulus Waveform: Isochronous Tones (Inter-Onset Interval = 500 ms)



Note. This is an inter-onset interval (IOI) that is constant at 500 ms, and the stimulus waveforms are aligned appropriately (isochronous tones).

Figure 3b.

Stimulus Waveform: Non-Isochronous Tones (Inter-Onset Interval = 500 ms)



Note. This is an inter-onset interval that is not constant at 500 ms as the stimulus waveforms are staggered (non-isochronous tones). As a result, these data were excluded from the analysis.

EEG was recorded using a 64-channel actiCHamp Plus system (Brain Products, GmbH, Gilching, Germany) with the international 10-20 montage. Horizontal Electro-oculogram (EOG) signals were recorded from electrodes placed at the outer canthi of the left and right eyes; vertical EOG signals were recorded from FP1 (upper) and an electrode below the left eye (lower). The electrode data were collected using BrainVision with a 1000 Hz sampling rate, and impedances were kept below 25 k Ω . The ground electrode used as the reference electrode for impedance measurement was placed at position FPz. The EEG data are referenced to the left mastoid and re-referenced to the average of the left and right mastoids. First, quality assurance was conducted to ensure the tones were isochronous and had an inter-onset interval of 500 ms (Figure 3a). Only 51 of the original 93 participants passed this test; the rest were excluded. The data from Figure 3b represent non-isochronous tones and were therefore excluded from the analysis.

The EEG data were processed using EEGLAB (Delorme & Makeig, 2004) in MATLAB (The MathWorks, Inc., 2023) with the FieldTrip toolbox (Oostenveld et al., 2011). EEG data were downsampled to 250 Hz for processing in MATLAB to reduce computational load and storage demands, while maintaining sufficient temporal resolution for beta-band activity. Independent component analysis (ICA) was used to remove artifacts. This process included removing bad channels and high-amplitude noise bursts from the pre-ICA dataset (preprocessed files), performing independent component analysis (ICA) on the cleaned pre-ICA dataset, loading the analysis dataset and corresponding filter, removing bad channels and noise bursts from the less-filtered analysis dataset, and subsequently applying the ICA weights derived from the pre-ICA dataset to the analysis dataset. Data from the left and right auditory cortices were the main data points for analysis, as shown in Figure 2.

Time-Frequency Analysis

The time-frequency analysis followed the approach of Chang et al. (2021), which used the EEGLAB toolbox's `newtimef` function. This program computes averages of EEG data from multiple electrodes (Delorme & Makeig, 2004). The first epoch of the recording was removed, and the remaining EEG epochs lasted 11 seconds each (Chang et al., 2021). Each epoch consisted of 20 isochronous tones, with 0.5 s buffers between them to limit artifact interference. Chang et al. (2021) define the beta band as 15-25 Hz to remain consistent with previous literature, as bands below 15 Hz or above 25 Hz are associated with the alpha and gamma bands, respectively. These bands are not relevant to this study; therefore, they were excluded from the data analysis. This study used a Fourier transform of the beta power time course at a 2 Hz presentation rate to analyze beta power oscillations across trials.

Statistics

Beta power entrainment activity difference between groups was analyzed in rhythmic conditions using a nonparametric, cluster-based permutation test with the FieldTrip toolbox, similar to the approach used by Chang et al. (2021) (Oostenveld et al., 2011). This procedure reduces the number of multiple comparisons by testing the statistical differences at the time and frequency clusters instead of individual time and frequency points. A cluster-based analysis is appropriate for this study, as it does not rely on assumptions about distribution. We performed a t -test between the groups AWS and ANS, and CWS and CNS, for each time or frequency sample as the initial scan for clustering. Then, we grouped adjacent frequency (Figures 5C, 6C, and 7C) or time (Figures 5B, 5D, 6B, 6D, 7B, and 7D) samples reaching a threshold of $p < 0.05$ in the initial scan into single clusters and summed the t -values of all samples within each cluster as a cluster-level statistic. If there were no group differences observed, the clusters of the observed

data should resemble the data of the null distribution, and the final p-value was corrected to two-tailed.

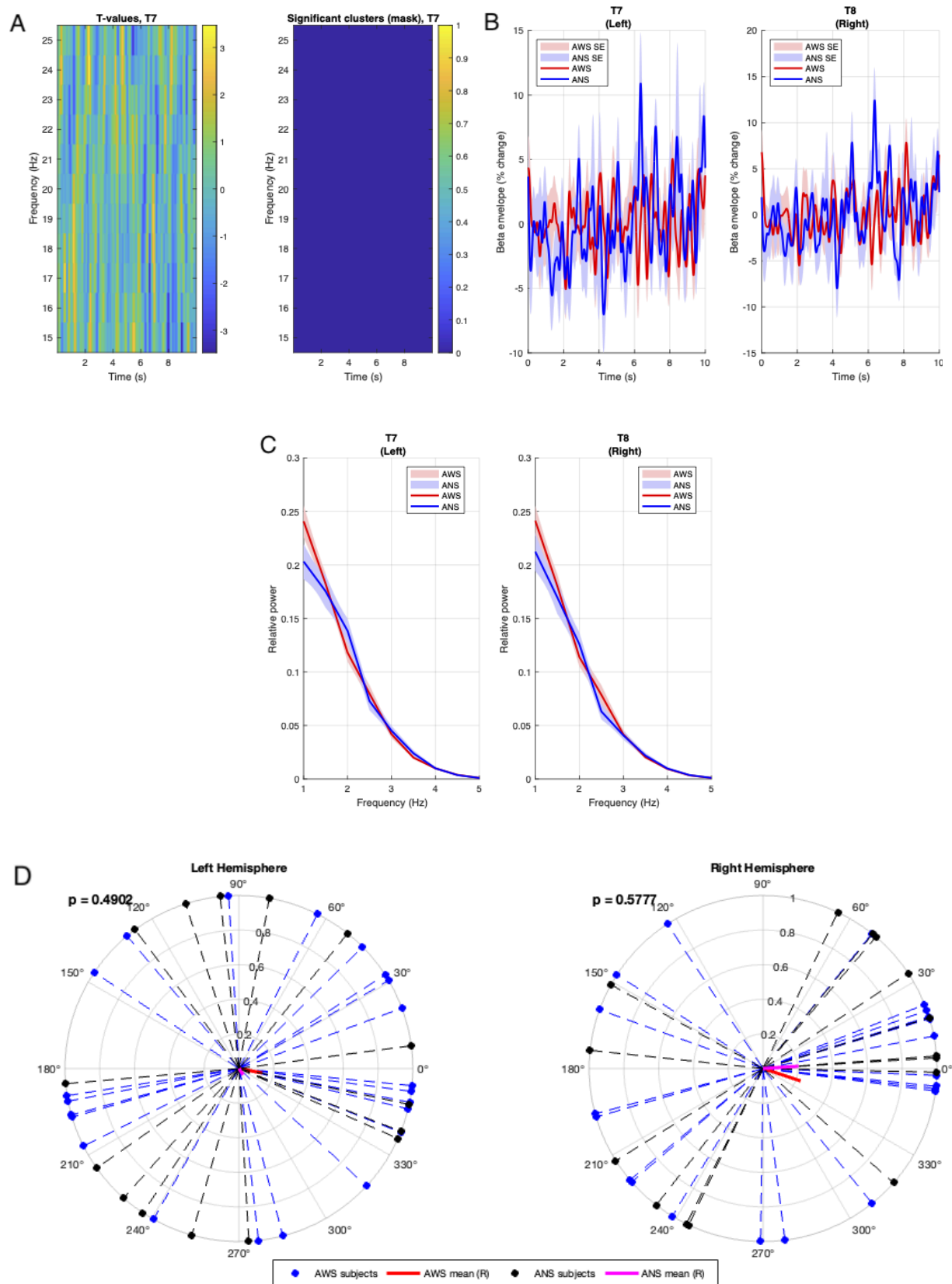
This study used a Watson-Williams two-sample test to compare the average phase angle of beta power fluctuations at the onset of each tone in the isochronous sequence. Note that the Watson-Williams test assumes the data to be distributed according to a von Mises distribution, where the concentration parameter (κ) is equal to or above 1. We specifically examined whether the phase of 2 Hz beta power fluctuation met this assumption. Although our data did not fully satisfy the assumptions, the Watson-Williams test is considered robust against the deviations in the data. The circular statistics in Figures 4D, 5D, and 6D were computed using the Circular Statistics Toolbox for MATLAB (Berens, 2009). Group differences (stuttering vs. controls and adults vs. children) for *R angle* and *length* of the arrows representing the group-averaged angle and consistency of the angle distribution were assessed with two-tailed independent tests.

Results

Final analyses were conducted with a sample of 51 participants. 42 participants were excluded due to non-isochronous tones in the stimulus waveform quality check or data file errors.

Figure 4.

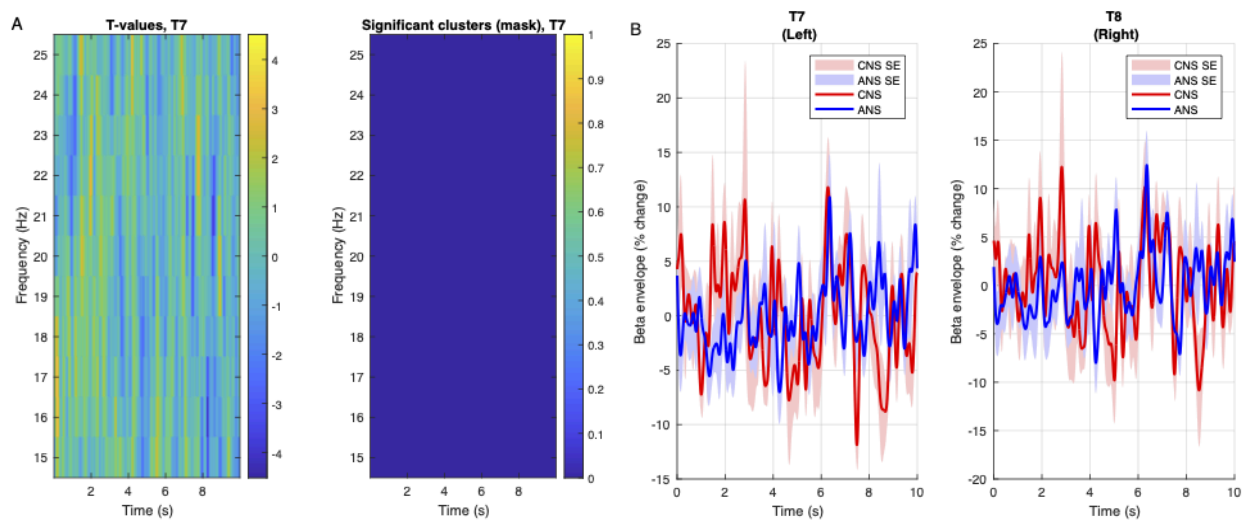
Beta Activity Comparisons Between AWS and ANS at Positions T7 and T8

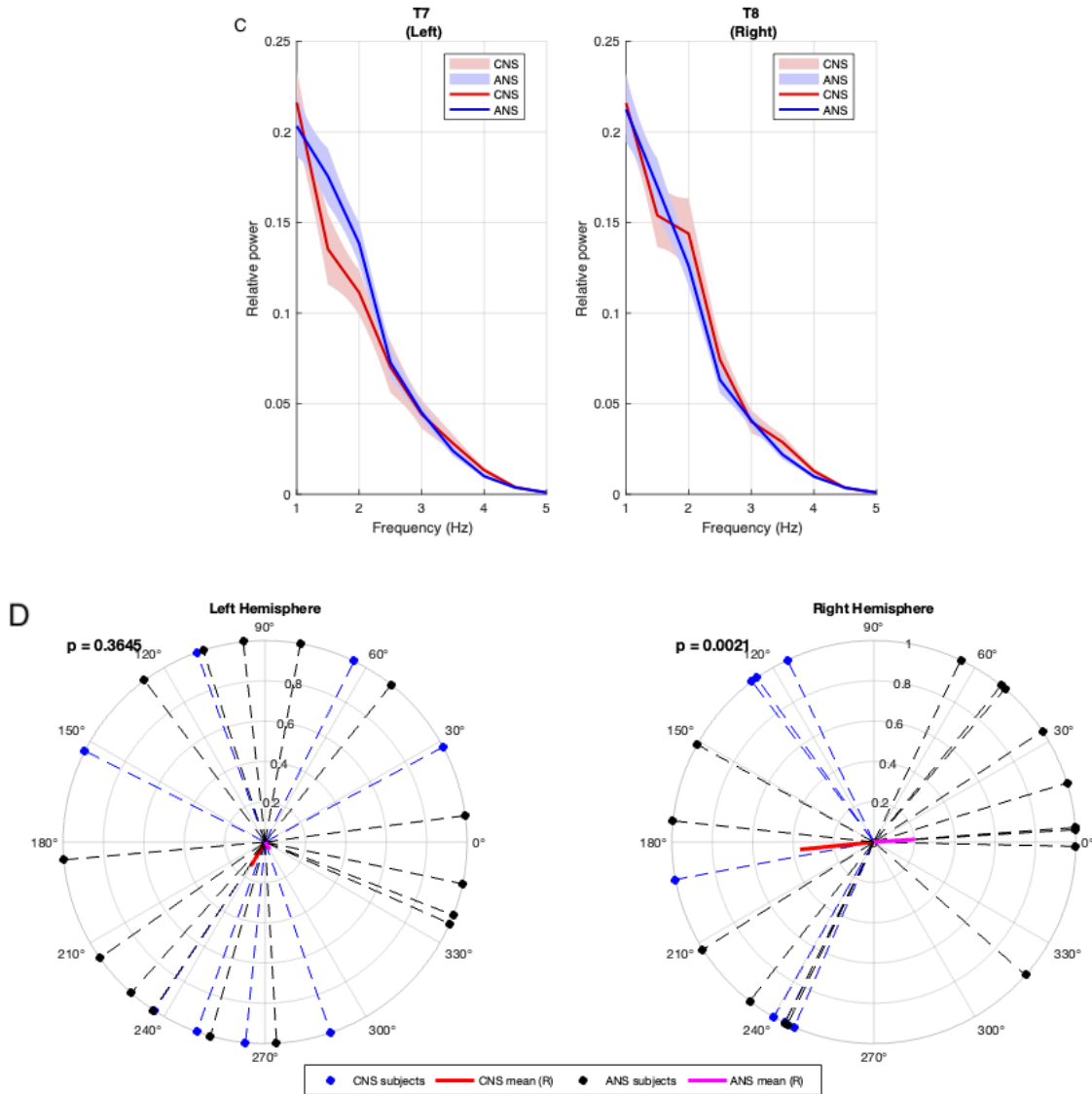


Note. (A) The group t -values and significant mask of frequency vs. time. (B) The beta power time series are presented as the mean $\pm$ standard error across typical (control) and participants who stutter. (C) The spectra of beta power fluctuation of relative power vs. frequency. (D) The phases of the beta power time series at 2 Hz. The beta oscillatory activity (15-25 Hz) in blue represents the AWS, as mean $\pm$ standard error, and the black activity represents the ANS. The phase angles and lengths of the red and pink arrows represent the group-averaged angle and consistency of the angle distribution (p: p-value).

Figure 5.

Beta Activity Comparisons Between ANS and CNS at Positions T7 and T8

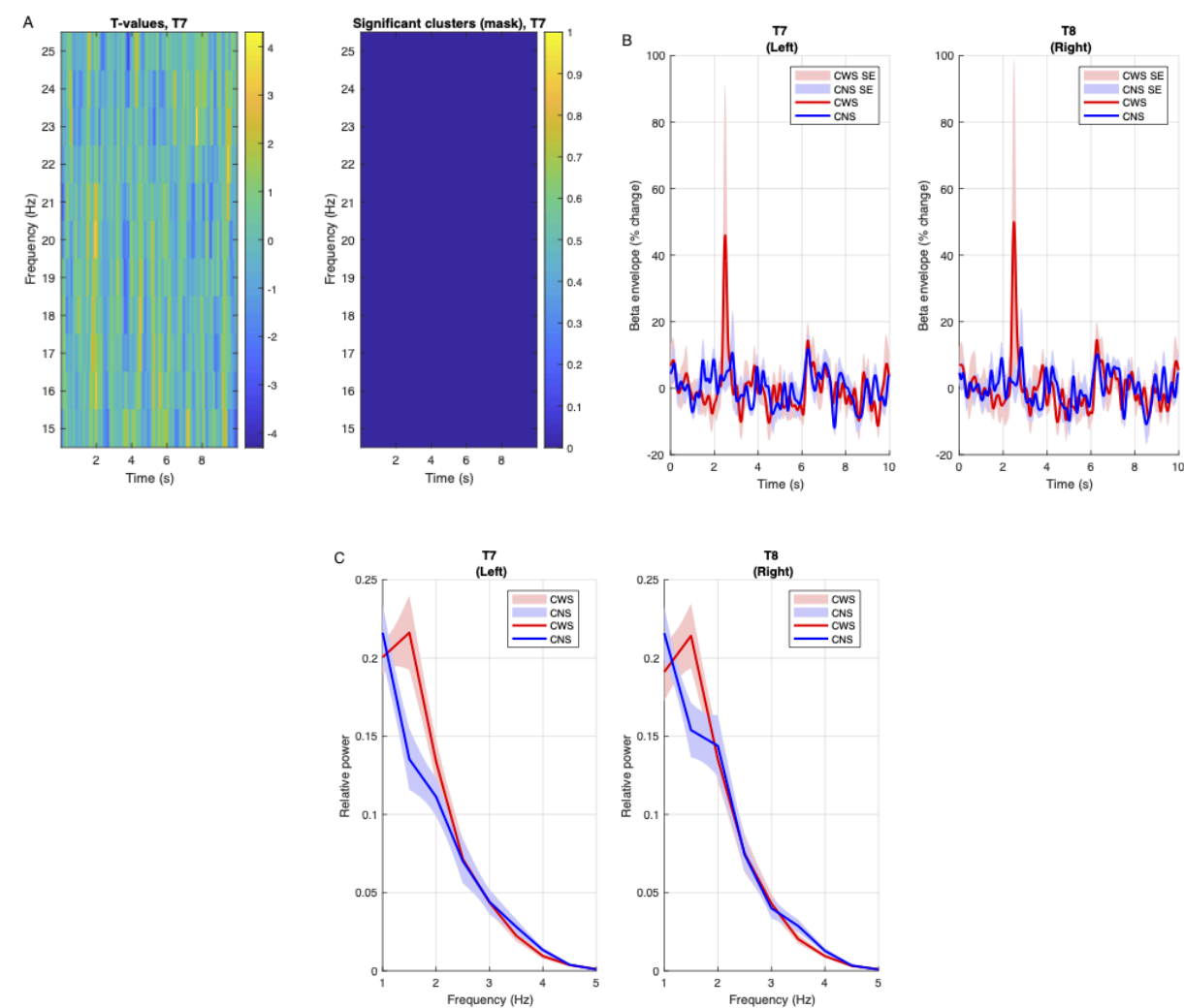


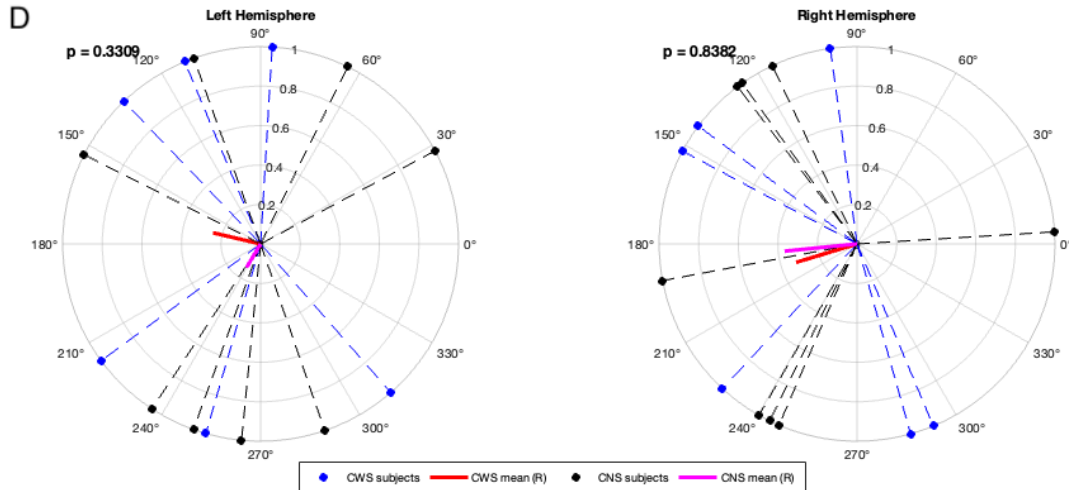


Note. (A) The group t -values and significant mask of frequency vs. time. (B) The beta power time series are presented as the mean $\pm$ standard error across typical (control) and participants who stutter. (C) The spectra of beta power fluctuation of relative power vs. frequency. (D) The phases of the beta power time series at 2 Hz. The beta oscillatory activity (15-25 Hz) in blue represents the CNS, as mean $\pm$ standard error, and the black activity represents the ANS. The phase angles and lengths of the red and pink arrows represent the group-averaged angle and consistency of the angle distribution (p: p-value).

Figure 6.

Beta Activity Comparisons Between CWS and CNS at Positions T7 and T8





Note. (A) The group t -values and significant mask of frequency vs. time. (B) The beta power time series are presented as the mean $\pm$ standard error across typical (control) and participants who stutter. (C) The spectra of beta power fluctuation of relative power vs. frequency. (D) The phases of the beta power time series at 2 Hz. The beta oscillatory activity (15-25 Hz) in blue represents the CWS, as mean $\pm$ standard error, and the black activity represents the ANS. The phase angles and lengths of the red and pink arrows represent the group-averaged angle and consistency of the angle distribution (p : p -value).

Beta Power

The beta-band power (15-25 Hz) and significant clusters are visualized in Figures 5A, 6A, and 7A. No significant differences in beta-band power were observed between AWS and ANS and CWS and CNS, at electrode position T7. Although the uncorrected t -value map showed scattered fluctuations across time (s) and frequency (Hz), cluster-based permutation testing revealed no significant clusters ($p > 0.05$). In other words, these differences were small, inconsistent, and did not survive correction for multiple comparisons. These findings indicate no significant group differences in beta oscillatory activity at T7.

AWS vs. ANS

The beta power time series of the left and right auditory cortices is visualized in Figure 4B at both T7 (left temporal) and T8 (right temporal). While the mean beta envelope (% change) for AWS and ANS overlapped substantially, these fluctuations were variable within each group, and standard error bands overlapped across the entire time window. There was no sustained temporal period in which one group consistently exhibited higher or lower beta power than the other, suggesting that temporal beta amplitude dynamics appear comparable between AWS and ANS. The spectra of beta power fluctuations are shown in Figure 4C, and the fluctuations did not demonstrate clear group separation. If a 2 Hz modulation peak was present, it appeared similar in magnitude across groups. Hence, rhythmic modulation strength at 2 Hz does not differ substantially between AWS and ANS at temporal sites. The phase analysis at 2 Hz is shown in Figure 4D, and the group-averaged phase angles and consistency (vector lengths) did not show divergence between AWS and ANS. If phase-locking was present, temporal beta oscillations phase-aligned to the 2 Hz rhythm appeared comparable across AWS and ANS. Across amplitude, spectral, and phase measures, there is no strong evidence for altered temporal beta oscillatory dynamics in AWS under the current task conditions ($p > 0.05$).

ANS vs. CNS

The beta envelope time series (% change) for ANS and CNS in Figure 5B shows substantial overlap across the recording interval. The fluctuations that appear in one group relative to the other are brief, inconsistent differences accompanied by overlapping standard bands. Temporal beta amplitude dynamics are broadly similar between ANS and CNS. The power spectra of beta envelope fluctuations in Figure 5C do not demonstrate a separation in modulation strength at 2 Hz. If both groups show a similar spectral peak at 2 Hz, this suggests comparable rhythmic modulation of beta oscillations. Hence, the developmental stage of the

participant (adult vs. child) does not appear to strongly alter the strength of rhythmic beta modulation in individuals who stutter. Phase analysis at 2 Hz in Figure 5D revealed a significant group difference at T8 (right auditory cortex) between ANS and CNS ($p = 0.0021$). Although beta amplitude and spectral modulation did not differ between groups, the temporal alignment of beta oscillations relative to the rhythmic stimulus was significantly altered in the right hemisphere. While no significant phase difference was observed at T7 (left auditory cortex), these findings suggest developmental changes in the right temporal beta timing in individuals who stutter.

CWS vs. CNS

The beta envelope time series in Figure 6B showed substantial overlap in mean amplitude with overlapping standard error bands and no sustained group separation. This suggests that temporal beta amplitude modulation is similar between CWS and CNS. The spectral analysis of beta power fluctuation in Figure 6C did not demonstrate clear group-specific differences in modulation strength within the border beta envelope fluctuation range (or at 2 Hz). CWS in these results do not show altered rhythmic modulation strength in temporal beta oscillations under this condition. The phase angle distributions at 2 Hz and consistency measures in Figure 6D did not indicate any separation between CWS and CNS. This suggests that the phase alignment of beta oscillations to rhythmic input appears comparable in CWS and CNS. Based on this evidence, CWS do not exhibit altered temporal beta oscillatory amplitude, modulation strength, or phase alignment relative to CNS at positions T7 or T8.

Overall Findings

The control groups did not show a statistically significant increase in beta oscillatory power relative to participants who stuttered at around 2 Hz when the stimulus was presented.

Both groups demonstrated comparable beta amplitude dynamics during the isochronous tone sequences, and cluster-based permutation analyses did not reveal significant power differences between groups. These findings suggest that the strength of beta power entrainment does not differ between individuals who stutter and those who do not under the experimental conditions. The phase analysis at 2 Hz revealed a significant difference in the right hemisphere when comparing ANS and CNS. While the beta power magnitude did not differ between groups, the temporal alignment of beta oscillations relative to the rhythmic stimulus differed developmentally. This suggests that beta oscillatory timing, rather than amplitude, may reflect meaningful neural differences within the stuttering population. These data do not support group differences in beta power entrainment between AWS and ANS and CWS and CNS. Although oscillatory timing differences were detected in the right hemisphere across age groups, further research with a larger sample is needed to determine whether these phase differences meaningfully relate to rhythm perception or the persistence of stuttering.

Discussion

This study aimed to investigate beta-band oscillatory activity (15-25 Hz) in the auditory cortex (with a focus on bilateral temporal sites T seven and T eight) and its relationship with the sensorimotor cortex in adults who stutter and those who do not. The EEG recording processed data from participants who listened to sequences of isochronous tones passively while watching a video on a screen in front of them. The data collected from this study were limited to 22 AWS, 15 adult controls, six CWS, and eight child controls, who were selected from the original 93 participants. These 51 participants provided data on beta oscillatory activity in the auditory cortex and the phase angles of the beta oscillations at two Hz using time-frequency analyses. Overall, we did not observe statistically significant group differences in beta power or phase

alignment at the two Hz stimulus rate between individuals who stutter and controls. However, a developmental difference in right-hemisphere phase was observed, suggesting developmental variation in the temporal alignment of beta oscillations rather than a stuttering-specific deficit. This suggests that basic auditory rhythm tracking, as indexed by beta oscillations, is preserved in individuals who stutter under passive listening conditions.

In adults, beta power and phase dynamics were broadly comparable between the AWS and control groups. Although some comparisons did not reach statistical significance, the absence of significant differences suggests that beta-band rhythmic entrainment during passive listening is largely preserved in AWS. Beta oscillations are widely implicated in temporal prediction and sensorimotor integration, particularly in rhythmic contexts (Arnal et al., 2015; Arnal & Giraud, 2012). Theoretical models of stuttering that implicate disruptions in the Cortico-Basal Ganglia-Thalamocortical loop (CBGTC) suggest that reduced beta entrainment may reflect impaired temporal prediction. However, the present findings do not provide evidence for altered beta entrainment under passive listening conditions. Oscillatory measures are sensitive to inter-individual variability, and small sample sizes may have limited statistical power. Together, these results suggest that timing-related differences in stuttering may not be detectable in passive auditory paradigms.

In children, beta power and phase measures were also comparable between CWS and CNS. Beta-band synchronization undergoes refinement across development, especially within the temporal and sensorimotor networks that support rhythmic perception and motor planning. Developmental EEG research suggests that the stability and functional specificity of these oscillations increase with age. If beta oscillations serve as neural markers of predictive timing (Arnal & Giraud, 2012), then the observed differences may instead reflect developmental

variability in neural timing mechanisms. Unlike adults who stutter, children who stutter have auditory and motor systems that are still consolidating. Neuroimaging studies have shown that structural and connectivity differences in speech-related networks are detectable early in development among children who stutter. For instance, young CWS show atypical white matter development in speech-language pathways compared with children who do not stutter (Chang et al., 2015). These findings suggest that neural markers of stuttering may exhibit structural differences that emerge during childhood and potentially contribute to later atypical neural activity, though these differences were not reflected in beta oscillatory measures in the current passive listening task.

This study aimed to replicate the findings of Chang et al. (2021) to determine whether the differences in beta oscillatory peaks and troughs between adults with dyslexia and control participants were analogous to those between adults who stutter and control participants. The lack of group differences in the present study suggests that findings from dyslexia may not directly generalize to stuttering, particularly under passive listening conditions. These results indicate that beta-based rhythmic tracking of isochronous tones is largely comparable between groups in this context. Future work is needed to determine whether task demands involving active motor engagement or auditory-motor coupling reveal group differences not observed here. Stuttering has been proposed to involve disruptions in sensorimotor coupling (Ladányi et al., 2020). However, the present findings do not provide evidence for impaired prediction of isochronous auditory timing under passive listening conditions, which supports the interpretation that such differences may be task-dependent rather than universally present.

Limitations

The most significant limitations of this study were the small sample size and the imbalance in the ratio between the stuttering and non-stuttering groups. The relatively small sample size reduced the ability to detect true group differences, especially the developmental variability in the child participants, and studies such as this aim to have an even number of participants who stutter and those who do not. Recruiting participants for this study is challenging across all age groups, particularly among adults who stutter. Unequal group sizes may also reduce statistical power and stability of estimates.

In addition, a substantial proportion of the initial dataset was excluded following quality control procedures (e.g., non-isochronous stimulus presentation), resulting in a reduced final sample size. While these steps were necessary to ensure data integrity, they may have further limited statistical power to detect subtle group differences. Given the high variability within stuttering populations, including differences in severity, persistence vs. recovery (children), and compensation strategies (adults), this may explain why within-group variability was high, and effects did not reach statistical significance. The EEG spatial limitations in the T seven and T eight positions should also be considered, as stuttering has been associated with neural circuits involving frontal, motor, and subcortical regions, including the basal ganglia and supplementary motor area. Localization of neuronal activity makes various assumptions that can limit data analysis; however, this method is efficient for determining the origin of signals recorded from electrodes.

Despite these limitations, the present study provides preliminary evidence that beta-band rhythmic entrainment during passive listening is largely comparable between individuals who stutter and controls, highlighting the importance of task context when interpreting neural timing differences.

Conclusion

This study did not find robust differences in beta oscillatory power at two Hz between the stuttering and control groups. However, a significant right-hemisphere phase difference between adults and children suggests that alterations in the timing of beta oscillations, rather than their amplitude, may characterize neural processing across development. The present findings do not provide evidence for reduced beta activation or impaired rhythm discrimination under passive listening conditions, and instead suggest preserved beta-based temporal tracking of isochronous auditory input (Fujioka et al., 2012). Future studies should examine larger samples and incorporate tasks involving active speech production or sensorimotor integration. While the current study was limited by sample size and data exclusion, future work should also examine beta oscillatory patterns beyond auditory cortex regions and investigate delta-beta interactions, which have been implicated in hierarchical temporal predictions and may be relevant for speech timing in stuttering. Temporal predictions are directly related to delta-beta-coupled oscillations in the auditory and motor cortices, as delta oscillations must also be at an optimal level for high-performance rhythm discrimination of isochronous tone sequences pre-stimulus onset (Arnal et al., 2015). Overall, these findings suggest that neural timing differences in stuttering may be context-dependent and may not be evident in passive auditory paradigms, and future work should clarify how these mechanisms relate to speech production and fluency. The lab currently has 65 adult participants (30 AWS and 35 control participants), and 28 child participants (18 CWS and 10 controls); data analysis for this study continues.

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