Neural & Behavioral Correlates of Speech and Melody Repetition in Aphasia

by

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ABSTRACT

Speech and music are traditionally thought to be primarily supported by different hemispheres. A growing body of evidence suggests that speech and music often rely on shared resources in bilateral brain networks, though the right and left hemispheres exhibit some domain-specific specialization. While there is ample research investigating speech deficits in individuals with right hemisphere lesions and amusia, fewer investigate amusia in individuals with left hemisphere lesions and aphasia. Many of the fronto-temporal-parietal regions in the left hemisphere commonly associated with speech processing and production are also implicated in bilateral music processing networks. The current study investigates the relationship between damage to specific regions of interest within these networks, and an individual's ability to successfully match the pitch and rhythm of a presented melody. Twenty-seven participants with chronic-stroke lesions were given a melody repetition task to hum short novel piano melodies. Participants underwent structural MRI acquisition and were administered an extensive speech and cognitive battery. Pitch and rhythm scores were calculated by correlating participant responses and target piano notes. Production errors were calculated by counting trials with responses that don't match the target melody's note count. Overall, performance varied widely, and rhythm scores were significantly correlated. Working memory scores were significantly correlated with rhythm scores and production errors, but not pitch scores. Broca's area lesions were not associated with significant differences in any of the melody repetition measures, while left Heschl's gyrus lesions were associated with worse performance on pitch, rhythm, and production errors. Lower rhythm scores were associated with lesions including both the left anterior and posterior superior temporal gyrus, and in participants with damage to the left planum temporale. The other regions of interest were not consistently associated with poorer pitch scores or production errors. Although the present study does have limitations, the current study suggests lesions to left hemisphere regions thought to only affect speech also affect musical pitch and rhythm processing. Therefore, amusia should not be characterized solely as a right hemisphere disorder. Instead, musical abilities of individuals with left hemisphere stroke and aphasia should be characterized to better understand their deficits and mechanisms of impairment.

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CHAPTER 1

INTRODUCTION

Scientists have been investigating the way in which we understand and produce speech and music for centuries, yet our understanding of these mechanisms remains incomplete. There exists much debate about the degree to which music and language share neural resources (Brown et al., 2006; Koelsch, 2011; LaCriox et al., 2015; Peretz & Zatorre, 2005). Research investigating amusia suggests that the right hemisphere is critical for music processing as it seems to be highly involved in pitch processing (Hyde et al., 2006; Kimura, 1964; Peretz & Hyde, 2003). Patel (2003) suggests a Shared Syntactic Integration Resource Hypothesis (SSIRH) which implicates a shared resource for syntax, or structure-building, in music and language in Broca's area with distinct processes for each modality related to both pitch and rhythmic aspects in the temporal lobes. Others suggest large networks of overlap between music and speech encompassing bilateral motor areas, bilateral auditory cortexes, and bilateral posterior cerebellum (Brown et al., 2006; Koelsch, 2011). A meta-analysis conducted on task-based fMRI studies of music and language suggests that the level of neural overlap between speech and music may be dependent on the type of task performed such that more cognitively demanding tasks recruit more bilateral frontal regions, whereas less demanding tasks are performed more laterally (LaCroix et al., 2015). There is consistent evidence for a degree of lateralization with music processing primarily taking place in the right hemisphere and language in the left hemisphere (Brown et al., 2006; Koelsch, 2011; LaCroix et al., 2015; Patel, 2003; Peretz & Zatorre, 2005).

For example, voxel-based lesion symptom matching analyses have shown that aphasia is traditionally associated with lesions in the left STG and insula, while amusia is related to the right STG, middle temporal gyrus, Heschl’s gyrus, putamen, and insula (Sihvonen et al, 2016). There is, however, evidence to suggest that right hemisphere lesions can lead to symptoms of aphasia, and less evidence to suggest that left hemisphere lesions lead to amusic symptoms (LaCoix et al., 2015; Marin & Perry, 1999; Patel, 2005). Combined with previously mentioned functional imaging data that suggest bilateral recruitment of fronto-temporal-parietal regions, it is likely that speech and music, to some degree, share neural resources. It has been suggested that the left hemisphere may be more fine-tuned to temporal structures and the right hemisphere may be more tuned for pitch processing (Peretz & Hyde, 2003).

By utilizing techniques such as lesion-symptom mapping in individuals with aphasia, we can highlight the anatomical structures that drive essential functions in producing or understanding language and music. There are many different tests that clinicians utilize to determine the specific pattern of speech-related deficits that an individual is facing in their post-stroke aphasia. This helps to determine the course of speech therapy. There is a lack of comparative measures for musical abilities, leading musical abilities to be understudied in individuals with aphasia even though there is evidence that suggests music-based therapies are beneficial for reversing certain deficits in language abilities and even motor abilities caused by stroke damage (Agustus et al., 2018; Ripollés et al., 2016). A major goal of this project is to develop an objective, quantitative procedure to analyze performance on a melody repetition task, including both pitch and rhythm domains. The current study then aims to combine these measures with magnetic resonance imaging (MRI) data to identify how pitch and rhythm deficits are related to damage in brain regions frequently implicated in speech tasks. The goal is that the findings will provide insight into the understudied music deficits that may be present in patients with aphasia.

Another goal of the current study is to implicate regions of interest in the left hemisphere traditionally thought to process speech in music processing. For example, while Broca's area mainly processes language, there is evidence to suggest that Broca’s area may be utilized in conjunction with its right hemisphere homolog in processing music (Kunert et al., 2015). We therefore expect to see melody repetition scores, specifically rhythm repetition scores to be lower for individuals with lesion sites in Broca’s area as speech processing is thought to rely on temporal processing in Broca’s area (Koelsch, 2011; Zatorre et al., 2002). Previous work has implicated bilateral Heschl’s gyrus in pitch processing as well as processing unfamiliar melodies (Agustus et al., 2018; Patterson et al., 2002). There is also evidence to suggest that bilateral Heschl’s gyrus areas are recruited for singing more than speaking, although more in the right Heschl’s gyrus than the left (Özdemir et al., 2006). We predict that nonword repetition scores and melody repetition scores will be lower for individuals with lesions in the left Heschl’s gyrus than for individuals with Heschl’s gyrus intact, though we expect to see impairments in speech repetition as well as melody repetition.

Previous literature implicates a bilateral dorsal medial temporal network that extends into the inferior parietal lobule in processing musical stimuli (LaCroix et al., 2015). Other work suggests that the bilateral inferior parietal lobule is more active during the encoding, maintenance, and retrieval of rhythm information (Konoike et al., 2012). Along with processing rhythmic information, the bilateral inferior parietal lobule may work in conjunction with the bilateral inferior frontal gyrus, bilateral supplemental motor areas, and the bilateral cerebellum to control motor movements, implying that the bilateral inferior parietal lobule is an area of sensory-motor integration, a function that is utilized in replicating rhythm (Konoike et al., 2012). We therefore expect to see lower rhythm repetition performance on the melody repetition task for individuals with lesions in the left inferior parietal lobule.

The bilateral superior temporal gyrus (STG) is a region known to be involved in auditory processing including language, melody, and pitch processing (Gaab et al., 2003; Patten, McBeath, & Baxter, 2018; Patterson et al., 2002; Sihvonen et al., 2016). While there is laterality of the STG such that we see amusia associated with right STG lesions and aphasia associated with left STG lesions, research in healthy individuals does suggest that the left STG plays a role in rhythm processing (Konoike et al., 2012; Sihvonen et al., 2016). Bilateral STG has also been implicated in melody processing and pitch working memory (Gaab et al., 2003; Patterson et al., 2002). We expect to see that lesions in the left STG will be associated with lower melody repetition, specifically on rhythm performance. There is also evidence to suggest that the right anterior STG (aSTG) and posterior STG (pSTG) play different roles in auditory processing such that the right aSTG is more involved in rhythm and the right pSTG more involved in pitch (Sihvonen et al., 2016). We hypothesize that individuals with lesion locations in the left aSTG will have lower rhythm performance and those in the left pSTG to have lower pitch performance.

Another brain region that has been implicated in the larger network of music processing is the bilateral planum temporale (PT) (Agustus et al., 2018 & Patterson et al., 2002). The bilateral PT may be a ‘hub’ of melody processing which may be responsible for receiving incoming auditory information and finding a stored template that matches (Agustus et al., 2018). For example, a familiar melody would cause the PT to search for and find the pitch and rhythm patterns stored in memory that match the current melodic pattern, but an unfamiliar melody would result in a failed search for a matching template in memory. Patterson and colleagues (2002) suggest that the PT is involved in pitch processing, in particular. Another postulated role of the left planum temporale is in phonological processing (Binder et al., 1996) We therefore expect to see that there will be lower melody and nonword repetition performance for individuals with lesion locations in the PT.

The cerebellum is also thought to be involved in music processing, particularly rhythm. The cerebellum is highly integrated with the motor networks of the brain (Gaab et al., 2003; Konoike et al., 2012; LaCriox et al., 2015). The left cerebellum has been implicated in music discrimination, music error detection, and music memory (LaCroix et al., 2015). The bilateral cerebellum has been shown to be activated during the encoding and retrieval of rhythmic information (Konoike et al, 2012). There is also evidence that suggests that the cerebellum plays a role in pitch memory and may act as a site for short-term pitch information storage (Gaab et al., 2003). We expect to see that individuals with lesion locations in the cerebellum will have lower performance scores on the pitch and rhythm subtests of the melody repetition task.

CHAPTER 2

METHODS

Participants

Participants included 27 individuals (13 females, 14 males) with chronic (at least 6 months post-stroke) stroke. All participants were right-handed, adults (*M* = 58, range 28-80), native American English speakers. Individuals were all right-handed before stroke onset and presented with a range of aphasia diagnoses including conduction aphasia, Broca's aphasia, anomic aphasia, and dysarthria (Table 2). Hourly compensation was provided to participants for their time. All tasks were administered by a trained experimenter during a 3-hour testing session. All subjects completed a demographic questionnaire. A summary of this information is provided in Table 1.

Table 1

Participant Demographics and Lesion Locations

Participant	Sex	Age	Left Broca's area	Left Heschl's gyrus	Left Planum Temporale	Left Anterior STG	Left Posterior STG	Left Inferior Parietal Lobule	Right Cere-bellum
AZ1003	F	48							
AZ1006	M	60		X	X	X	X	X	
AZ1008	F	75	X	X			X	X	
AZ1012	M	77	X	X	X	X	X	X	
AZ1015	M	78							
AZ1016	M	37					X	X	
AZ1017	M	78							
AZ1018	F	43	X						
AZ1021	F	69							
AZ1023	F	47							
AZ1024	F	65							X
AZ1025	M	73							
AZ1026	M	70	X						
AZ1027	M	54							
AZ1028	F	80		X	X	X	X	X	
AZ1029	F	34	X	X	X		X	X	
AZ1030	M	56						X	
AZ1031	F	40	X						
AZ1032	M	28						X	
AZ1034	F	59					X	X	
AZ1035	F	41							
AZ1037	M	57	X						
AZ1039	F	66							
AZ1040	F	54							
AZ1044	M	65							X
AZ1045	M	61					X	X	
AZ1046	M	50							

Note: Mean age = 58, range 28-80. "No scan" indicates that MRI acquisition was not completed for that participant.

Table 2

Aphasia Diagnosis of Each Participant

Participant	Aphasia Type	Participant	Aphasia Type	Participant	Aphasia Type
AZ1003	Broca's	AZ1023	None	AZ1032	Anomic
AZ1006	Broca's	AZ1024	None	AZ1034	Anomic
AZ1008	Broca's	AZ1025	None	AZ1035	Broca's
AZ1012	Wernicke's	AZ1026	None	AZ1037	Broca's
AZ1015	None	AZ1027	None	AZ1039	Anomic
AZ1016	Broca's	AZ1028	Wernicke's	AZ1040	Broca's
AZ1017	None	AZ1029	None	AZ1044	Dysarthria
AZ1018	Broca's	AZ1030	Broca's	AZ1045	Conduction
AZ1021	Anomic	AZ1031	Broca's	AZ1046	Broca's

Data Collection and Lesion Mapping

T1 images were collected using a 3T Phillips Ingenia MRI scanner with a 32 channel radiofrequency head coil at the Keller Center for Imaging Innovation at the Barrow Neurological Institute located in Phoenix, Arizona. Lesion maps were manually drawn on T1 images using MRIcron. Lesion maps were separated into regions of interest using structural-anatomical boundaries and brain atlases. The regions of interest are Broca's area, left planum temporale, left Heschl's gyrus, left anterior superior temporal gyrus, left posterior superior temporal gyrus, left inferior parietal lobule, and the right cerebellum. These regions were chosen based on previous literature implicating them in music processing as well as *a priori* hypotheses that these sites will affect melody repetition.

Measures

Melody Repetition Task

The melody repetition task consists of 10 novel piano melodies in C major that are repeated 3 times in succession for participants for a total of 30 trials. All melodies are 5 to 8 notes long and last 3 seconds in duration. Participants were asked to listen to a melody and repeat what they hear by singing the melody with a single syllable (i.e., “la” or “da”). Responses were recorded via a video recorder. Sound files were later extracted from the video for further analysis.

Nonword Repetition Task

Participants were administered an extensive speech battery; we focus on the Philadelphia nonword repetition task (Roach et al., 1996) here because it is perhaps the best correlate of the melody repetition task in the speech domain The task consists of 60 nonwords that contain a different number of real phonemes. Nonwords were presented via headphones and participants were asked to repeat them aloud. A nonword repetition was considered correct if each phoneme was intelligible and matched the target phonemes of the presented nonword, as determined by a trained research assistant. Total scores were divided by the total number of trials to yield a proportion correct score.

WAIS *(Wechsler Adult Intelligence Scale)*

The WAIS was administered to all but one subject as they declined further testing. The processing speed and working memory indexes were utilized in the present study. The processing speed index is a measure of mental speed and includes three tasks: coding, symbol search, and cancellation. It is important to note that processing speed scores can be affected by general attention. The working memory index is a measure of an individual's ability to hold and manipulate information and includes a digit span, letter-number sequencing, and arithmetic tasks.

Processing of Melody Repetition Data

Recordings of the melody repetition task were imported into Praat software where each response was segmented into individual utterances, representing notes. All silences over 500ms were left out of the analysis. Data were then imported into MATLAB. The MATLAB script ran another program, Praat, with a pitch tracking tool. All recordings were run through the pitch tracking twice, the first run provided minimum and maximum pitch estimates that were used as limits for the second run. This was done to improve the accuracy of the pitch estimation. Average pitch was calculated for each utterance along with the duration of each. We also calculated the number of utterances produced for each melody. By subtracting the number of notes in the original piano melody and the number of utterances, we determined if the participant made a production error. If the number of produced utterances was not equal to the number of notes present in the original melody, that trial was marked as having a production error. These production errors were used to weight pitch and rhythm scores such that responses with errors had a lower weight, reducing their impact on scores.

To obtain a measure of pitch performance, correlation values were calculated for each utterance by correlating it to the corresponding target piano pitch which was also extracted via Praat and MATLAB. These correlation values were averaged over melody and over all trials for a composite pitch performance score. Similar analyses were performed to obtain a rhythm score where rhythm performance was calculated by averaging correlation values between utterance and target piano note duration.

Statistical Analyses

Pearson's correlations between scores on the melody repetition, nonword repetition, working memory index, and processing speed index were calculated using the International Business Machines Statistical Package for the Social Sciences (SPSS 28). To test the hypotheses regarding our regions of interest, Welch's independent-samples *t*-tests were conducted using SPSS between groups for a given measure (i.e. participants with damage in a given region of interest versus those that do not have damage), when at least each group included an n=5. For comparisons with groups of less than five participants, Bayesian single-case *t*-tests were used to compare each individual with damage in the region of interest against participants with lesions elsewhere in the left hemisphere using the singlebayes.exe open-source computer program (Crawford, 2005).

CHAPTER 3

RESULTS

Overall Performance

As expected in a heterogeneous sample of individuals with aphasia, there was a wide range of performance on all measures of the melody repetition task, and nonword repetition, as well as the working memory, and processing speed indices (Table 3, Figure 1). Average performance on the pitch subtest of the melody repetition task ($M = .21$, $SD = 0.19$) was lower than the average performance on the rhythm subtest ($M = .44$, $SD = 0.26$). Participants made production errors on over half (60%) of trials on average. As expected, the rhythm and pitch measures of the melody repetition task were significantly positively correlated: $r(25) = 0.52$, $p < .01$ (Figure 2).

Table 3

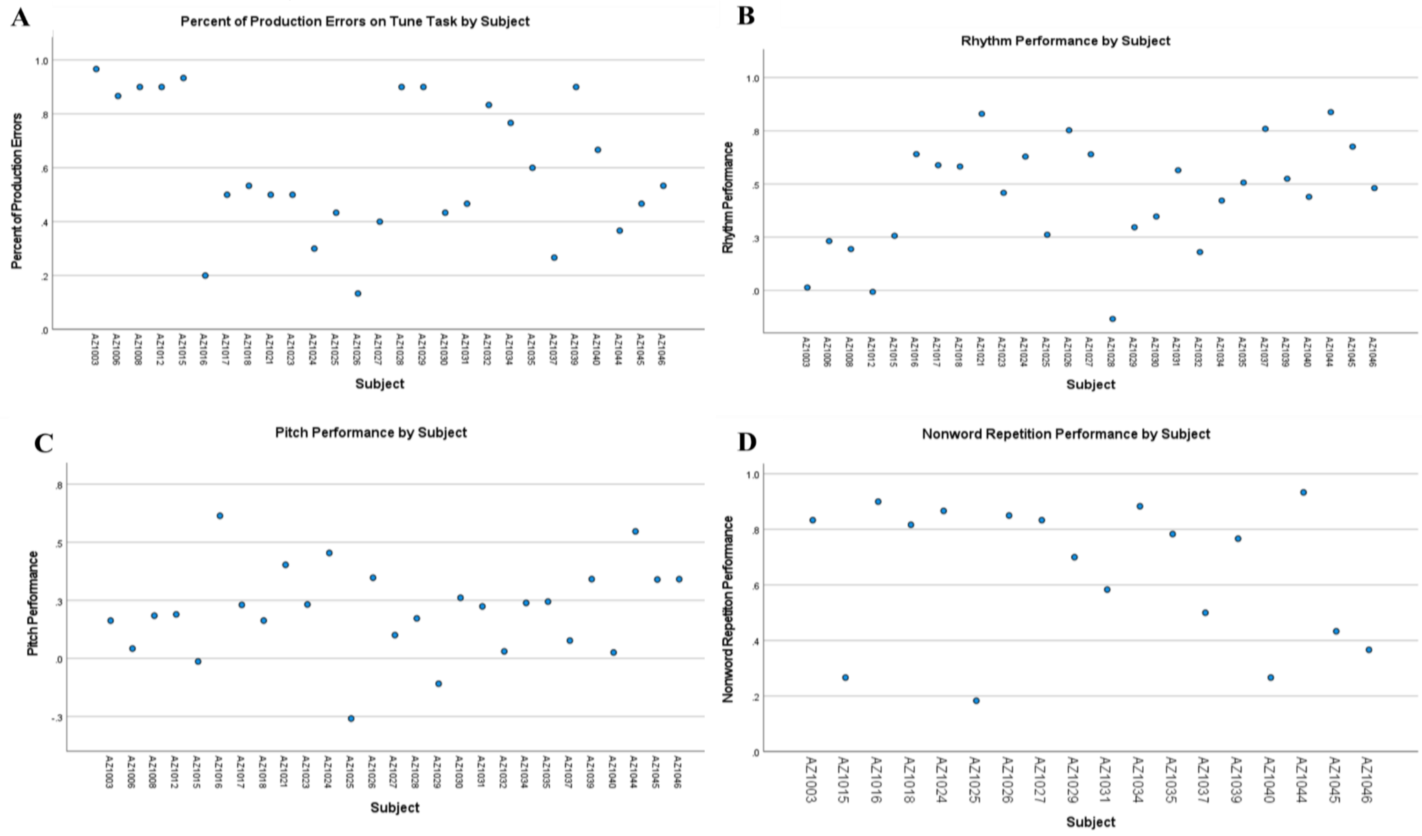
Descriptive Statistics of Performance Measures

	N	Mean	Standard Deviation
Pitch Performance	27	0.21	0.19
Rhythm Performance	27	0.44	0.26
Production Errors	27	0.60	0.25
Nonword Repetition	18	0.65	0.25
Processing Speed Index	26	80.77	15.64
Working Memory Index	26	80.50	24.79

Note: Pitch and rhythm performance are correlation values between the participant's response and the target melody's pitch and rhythm, respectively. Production errors are measured by the percent of trials in which the number of notes produced by the participant did not match the number of notes in the target melody. Nonword repetition is measured by the percentage of nonwords (out of 60) that the participant correctly and intelligibly produced the nonword. Processing speed and working memory indexes were scored using the WAIS.

Figure 1

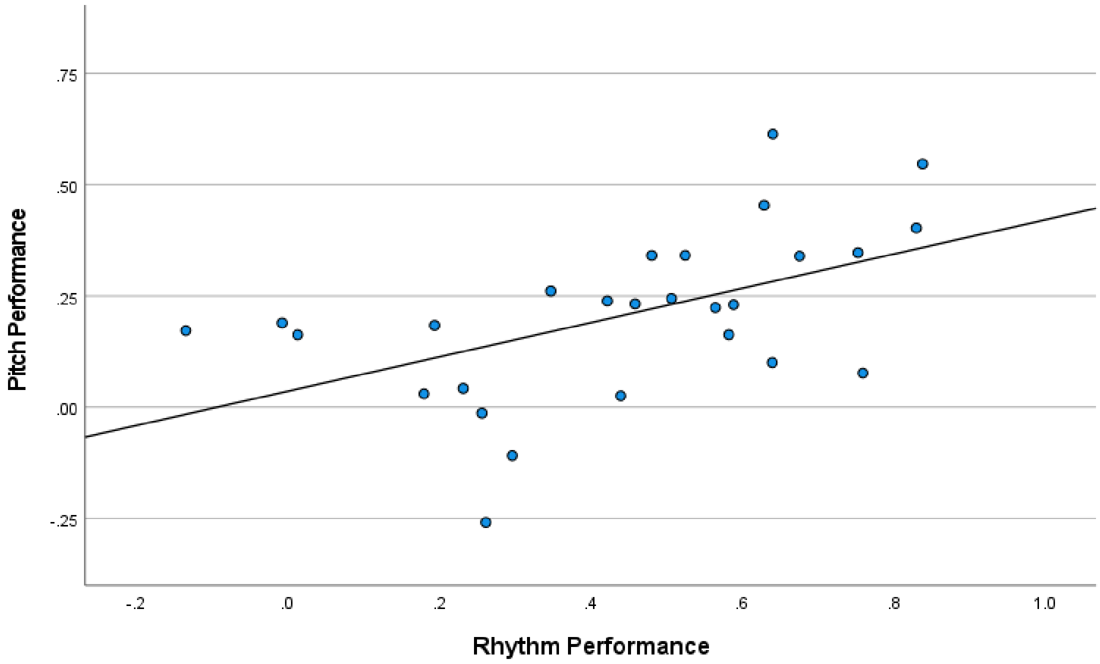
Performance on Melody Repetition Measures and Nonword Repetition Task



*Note: **A** Percentage of production errors performed on the melody repetition task by each participant. **B** Performance in the rhythm domain on the melody repetition task. **C** Performance in the pitch domain of the melody repetition task for each participant. **D** Percentage of nonwords correctly produced on the Philadelphia nonword repetition task*

Figure 2

Pitch Versus Rhythm Performance on the Melody Repetition Task



Relationship Between Melody Repetition and Cognitive Measures

Pearson correlations between the melody repetition task measures (pitch, rhythm, production errors) and the cognitive measures (working memory, processing speed) yielded the following results (Table 4): Pitch was not significantly correlated with working memory or processing speed. However, both rhythm and number of production errors on the melody repetition task were significantly correlated with working memory (Figures 3 and 4) but not processing speed - such that better performance on both the rhythm and production errors measures was associated with better working memory.

Relationship Between Melody Repetition and Speech Repetition

Pearson correlations computed between the melody repetition task measures and nonword repetition performance are summarized in Table 4. Pitch performance was significantly positively correlated with nonword repetition performance: and pitch performance $r(16) = 0.61$, $p < .01$. Rhythm and production errors were both not significantly correlated with non-word repetition performance.

Table 4

Correlations of Melody Repetition Task Measures and WAIS Subtests' Performance

Variable	Processing Speed	Working Memory Index	Nonword Repetition
Pitch Performance	0.15, *p* = .46	0.21, *p* = .31	**0.61, *p* = .01**
Rhythm Performance	0.09, *p* = .66	**0.49, *p* = .01**	0.32, *p* = .20
Production Errors	-0.03, *p* = .88	**-0.47, *p* = .01**	-0.16, *p* = .52

Note: df = 24 for correlations with processing speed and working memory index. Note: df = 16 for correlations with nonword repetition. Statistics ***in bold*** *are statistically significant, p < .05.*

Figure 3

Rhythm Performance on the Melody Repetition Task Versus Working Memory Index Scores

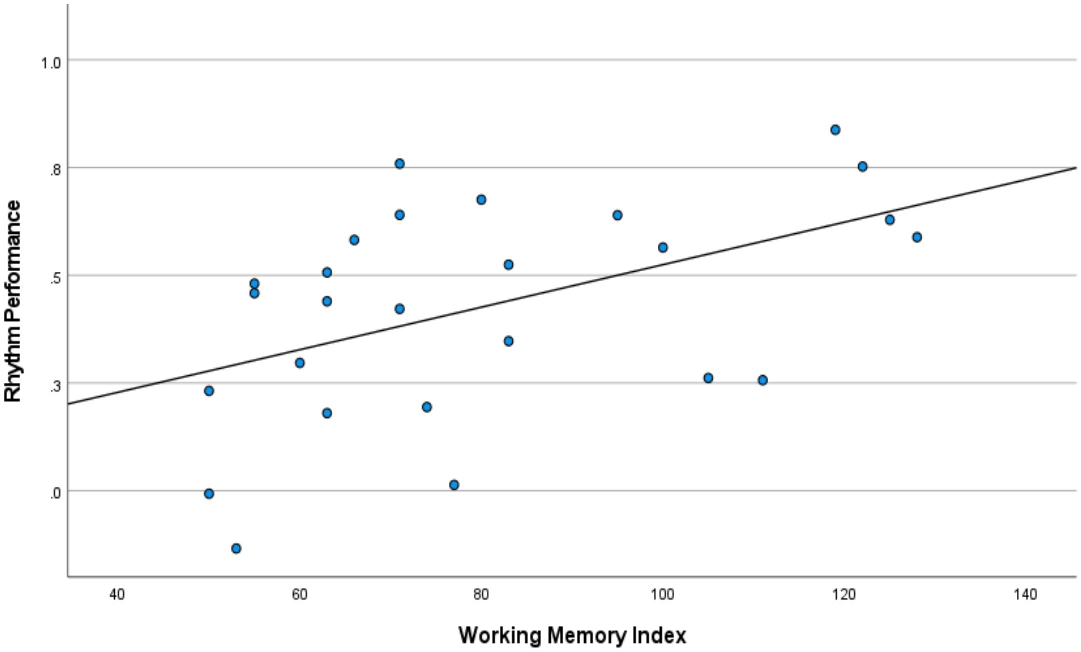
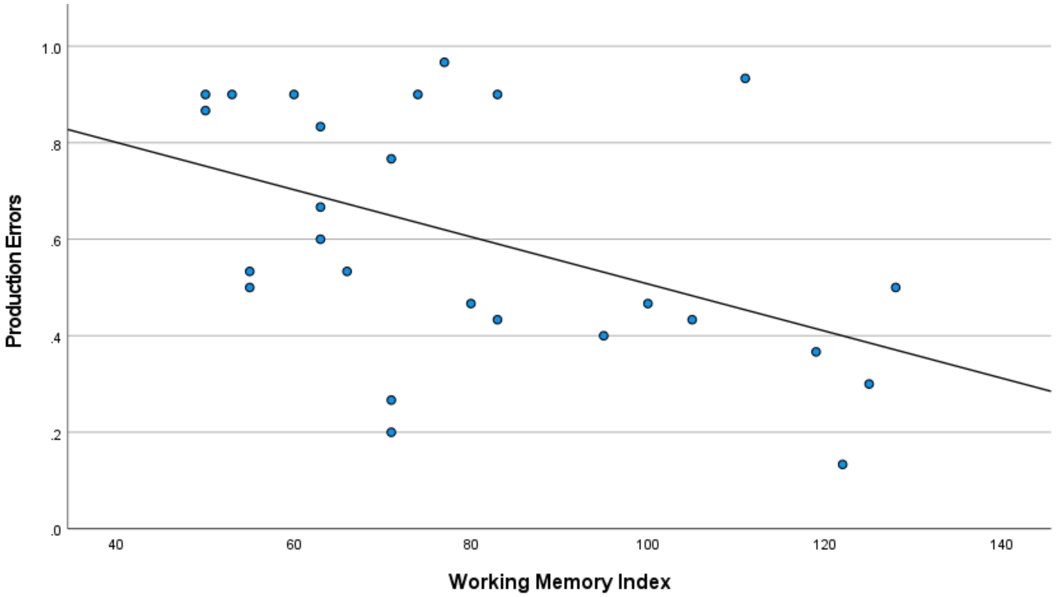


Figure 4

Production Errors on the Melody Repetition Task Versus Working Memory Index Scores

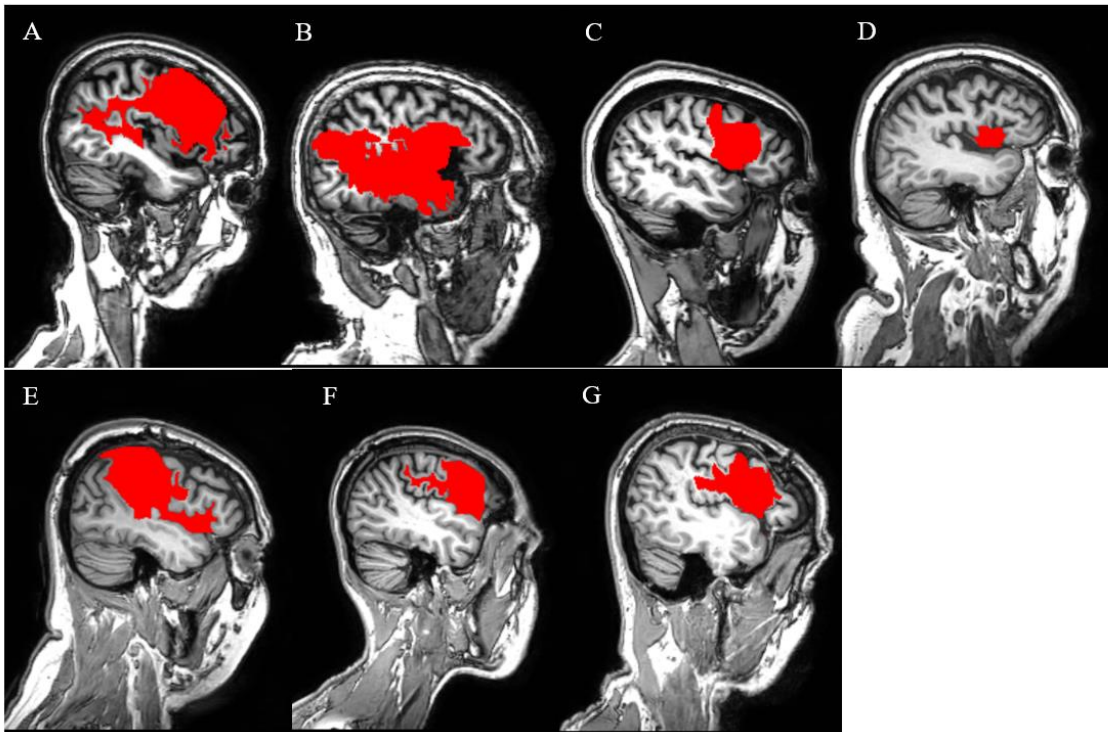


ROI-Based Analyses: Broca's Area

To test the hypothesis that melody repetition task scores, specifically rhythm scores, will be significantly lower in participants with lesions including Broca's area, compared to other participants with left hemisphere lesions, we conducted Welch's *t*-tests (Table 5). Contrary to our hypothesis, there were no significant differences identified between the two groups of participants on any of the melody repetition measures (Table 5; Figure 6).

Figure 5

Images of Lesion Locations of Participants With Lesions Including Broca's Area



Note: A) Participant AZ1008 B) Participant AZ1012 C) Participant AZ1018 D) Participant AZ1026 E) Participant AZ1029 F) Participant AZ1031 G) Participant AZ1037

Table 5

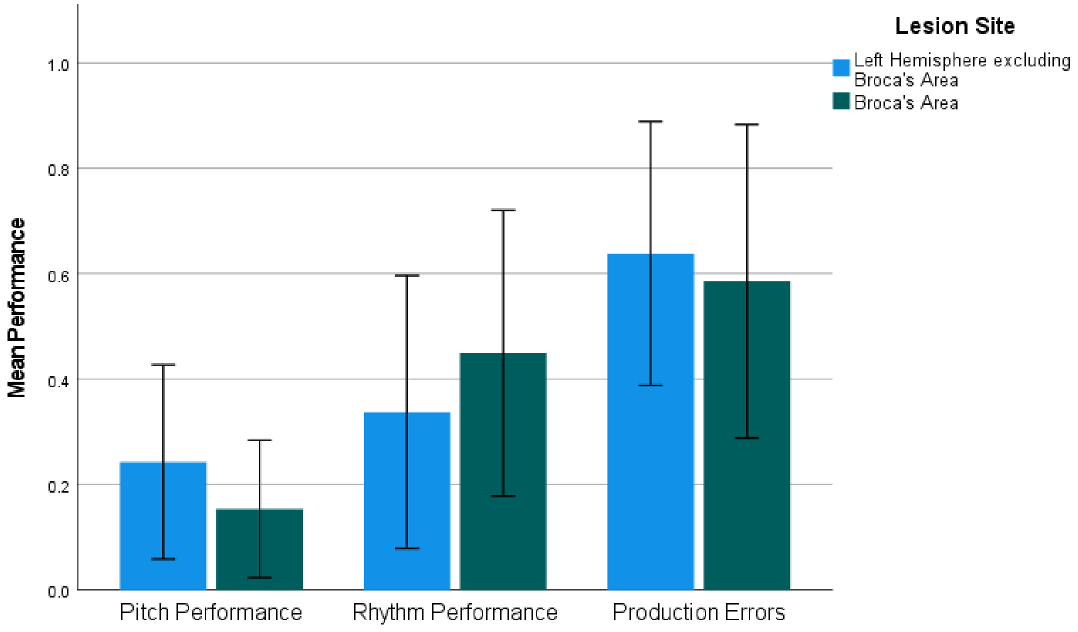
Differences Between Left Hemisphere and Broca's Area Participant Scores on Melody Repetition Task Subtests

	Left Hemisphere Lesions Excluding Broca's		Lesions Including Broca's Area					
	M	*SD*	*M*	*SD*	*df*	*t*	*p*	Cohen's *d*
Pitch Performance	0.24	0.22	0.15	0.14	10.82	0.97	0.18	0.17
Rhythm Performance	0.34	0.28	0.45	0.29	11.98	-0.73	0.24	-0.39
Production Errors	0.64	0.27	0.59	0.32	11.66	0.33	0.37	0.30

Note: Welch's independent samples t*-test statistics are reported as homogeneity of variance assumption was not met.*

Figure 6

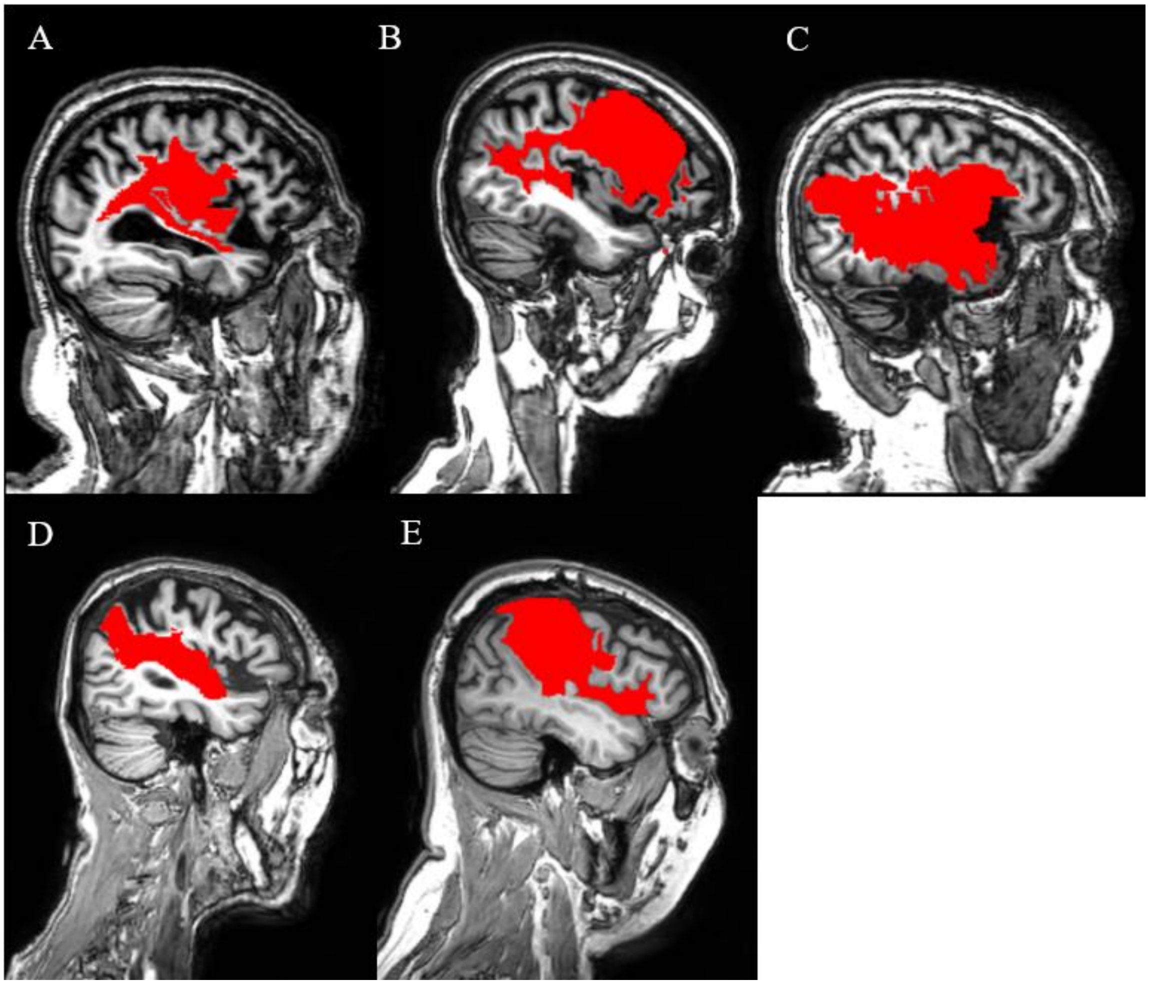
Performance on Melody Repetition Task Measures for Participants with Broca's Area and Other Left Hemisphere Lesion Sites



ROI-Based Analyses: Left Heschl's Gyrus To test the hypothesis that 5 participants with lesions in left Heschl's Gyrus would perform worse on both the melody and speech repetition tasks compared to participants with left hemisphere damage excluding Heschl's gyrus, we conducted a single-case Bayesian *t*-test (Crawford et al., 2005) for non-word repetition, since there was only one participant with damage to Heschl's gyrus that also completed the nonword repetition task. This *t*-test indicated that there was no significant difference in nonword repetition performance between the participant with Heschl's gyrus damage (n=1) and those participants with left hemisphere damage excluding Heschl's gyrus (n=7) (Table 6, Figure 8).

Figure 7

Images of Lesion Locations of Participants With Lesions Including Left Heschl's Gyrus



Note: A) Participant AZ1006 B) Participant AZ1008 C) Participant AZ1012 D) Participant AZ1028 E) Participant AZ1029

Table 6

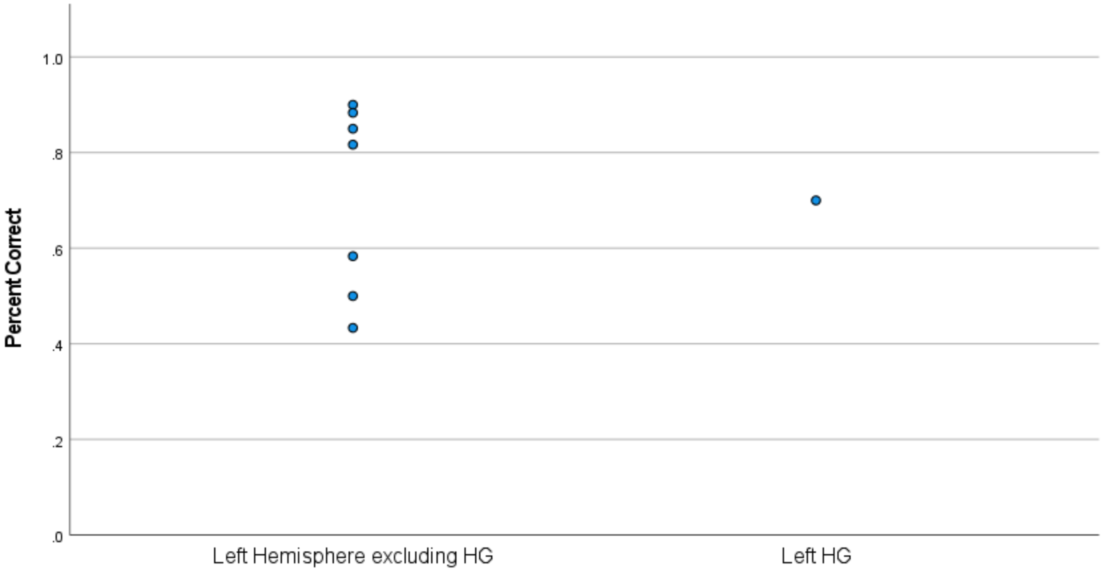
Bayesian T-Test Single-Case Comparisons of Nonword Repetition of Left Heschl's Gyrus and Other Left Hemisphere Lesion Sites

Participant	One-tailed *p*	Percent of Control Population Below
AZ1029	0.48	48.38%

Note. Results of the single-case Bayesian t-tests for nonword repetition. Percentages indicate a point estimate of the percentage of the control population that exhibits a lower nonword repetition score than the aphasia participant.

Figure 8

Nonword Repetition Scores for Left Heschl's Gyrus and Other Left Hemisphere Lesion Sites



Welch's *t*-tests were then computed to compare pitch, rhythm, and production error scores, respectively, between participants with lesions to the left Heschl's Gyrus (n=5) and other areas of the left hemisphere (n=9, Table 7). We did find a significant effect of damage in left Heschl's gyrus for all three melody repetition measures: pitch, $t(10.59) = 1.95$, $p = 0.04$, rhythm, $t(9) = 4.16$, $p = 0.001$, and production error, $t(8.11) = -5.5$, $p < .001$, (Table 7; Figure 9).

Table 7

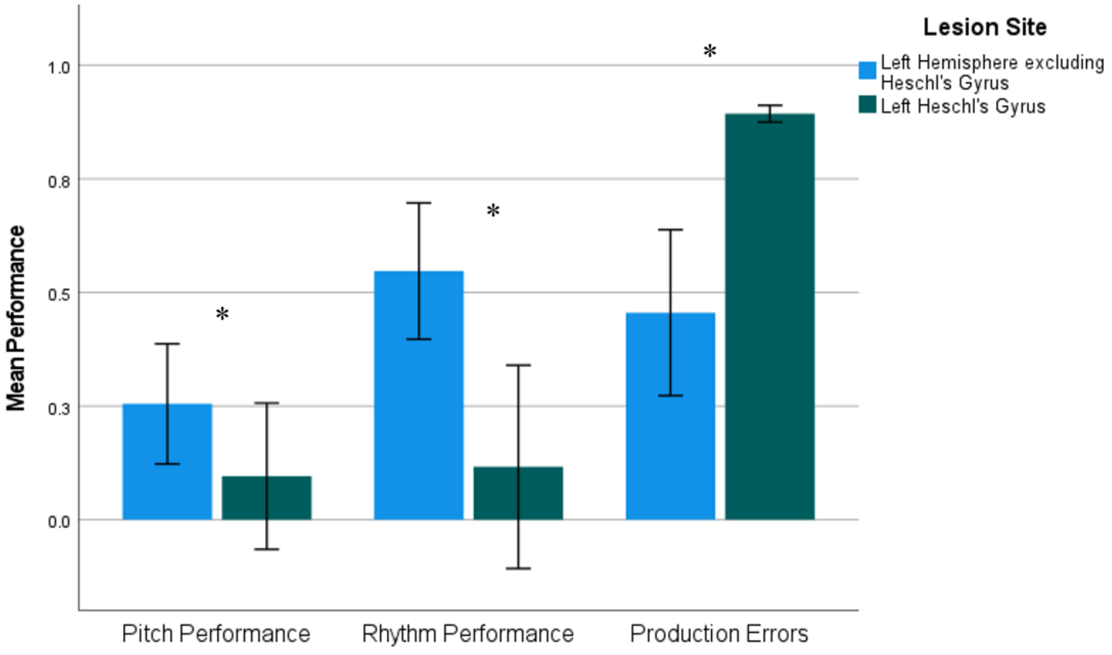
Differences Between Left Hemisphere and Left Heschl's Gyrus Participant Scores on Melody Repetition Task Subtests

	Left Hemisphere Lesions Excluding Heschl's Gyrus		Lesions Including Left Heschl's Gyrus					
	M	*SD*	*M*	*SD*	*df*	*t*	*p*	Cohen's *d*
Pitch Performance	0.25	0.17	0.10	0.13	10.59	1.95	**0.04**	1.00
Rhythm Performance	0.55	0.19	0.12	0.18	9.00	4.16	**.001**	2.27
Production Errors	0.46	0.24	0.89	0.01	8.11	-5.5	**<.001**	2.26

Note: Welch's independent samples t-test statistics are reported as homogeneity of variance assumption was not met. Bold indicates statistically significant at p< .05.

Figure 9

Performance on Melody Repetition Task Measures for Participants with Left Heschl's Gyrus and Other Left Hemisphere Lesions.



*Note: * = statistically significant difference*

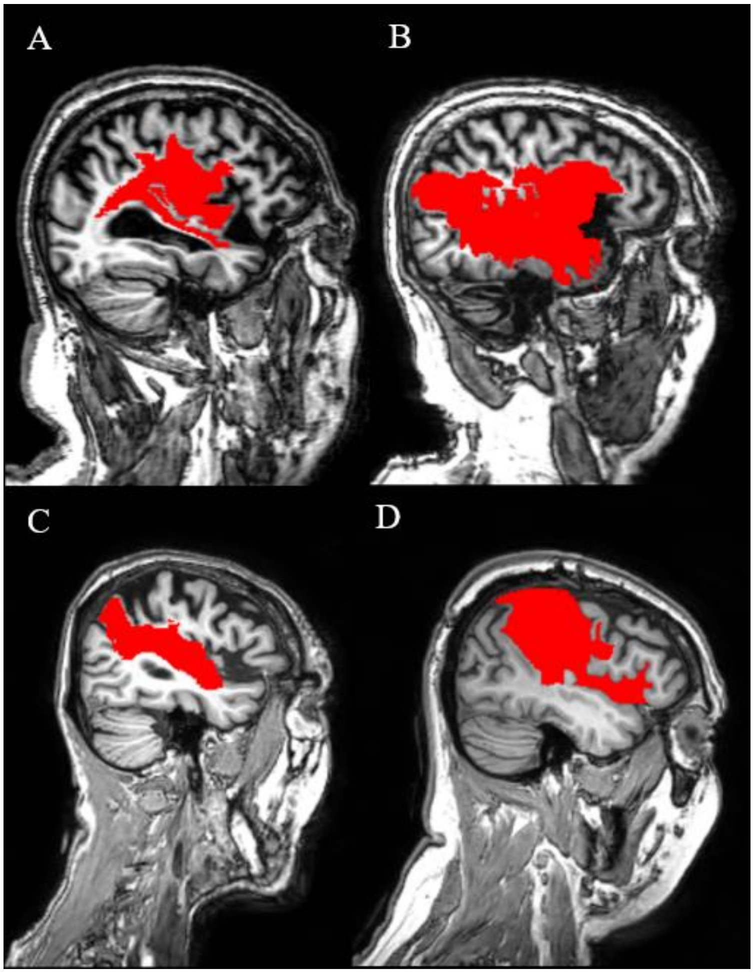
ROI-Based Analyses: Left Planum Temporale

To test the hypothesis that the planum temporale is critical for both melody and speech repetition, single-case Bayesian *t*-tests were conducted on melody and nonword repetition scores for each of the four participants with lesions to the left planum temporale, in comparison to the participants with lesion locations elsewhere in the left hemisphere (n=10). The results are summarized in Table 12. In short, there were no significant differences in production error scores in the melody repetition task (Figures 13 & 14) or nonword repetition scores (Figure 15).

However, the results for pitch performance indicate that participant AZ1029 scored significantly lower ($p = 0.03$) (Table 8, Figures 11 & 14). In addition, rhythm performance was significantly lower for two other participants with planum temporale damage: AZ1012 ($p = 0.02$) and AZ1028 ($p = .01$) (Table 8, Figures 12 & 14).

Figure 10

Images of Lesion Locations of Participants With Lesions Including Left Planum Temporale



Note: A) Participant AZ1006 B) Participant AZ1012 C) Participant AZ1028 D) Participant AZ1029

Table 8

Bayesian T-Test Single-Case Comparisons of Nonword and Melody Repetition Performance for Left Planum Temporale and Other Left Hemisphere Lesion Sites

	Pitch Performance		Rhythm Performance		Production Errors		Nonword Repetition	
Participant	*p*	%	*p*	%	*p*	%	*p*	%
AZ1006	0.17	83.35	0.12	12.30	0.11	89.11	-	-
AZ1012	0.37	36.99	**0.02**	**2.35**	0.09	90.87	-	-
AZ1028	0.33	33.46	**0.01**	**0.93**	0.09	90.87	-	-
AZ1029	**0.03**	**3.39**	0.18	18.27	0.09	90.87	0.48	48.29

Note. Results of the single-case Bayesian t-tests for melody and nonword repetition scores. Percentages indicate a point estimate of the percentage of the control population that exhibits a lower nonword repetition score than the aphasia participant. Bold indicates statistical significance at p < .05.

Figure 11

Pitch Performance Scores for Participants With Left Planum Temporale and Other Left Hemisphere Lesion Sites

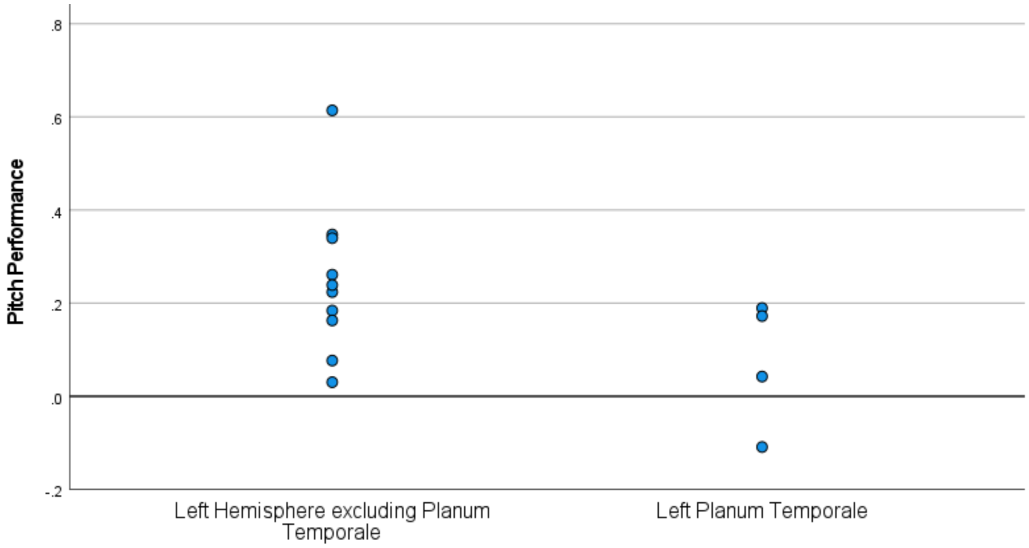


Figure 12

Rhythm Performance Scores for Participants With Left Planum Temporale and Other Left Hemisphere Lesion Sites

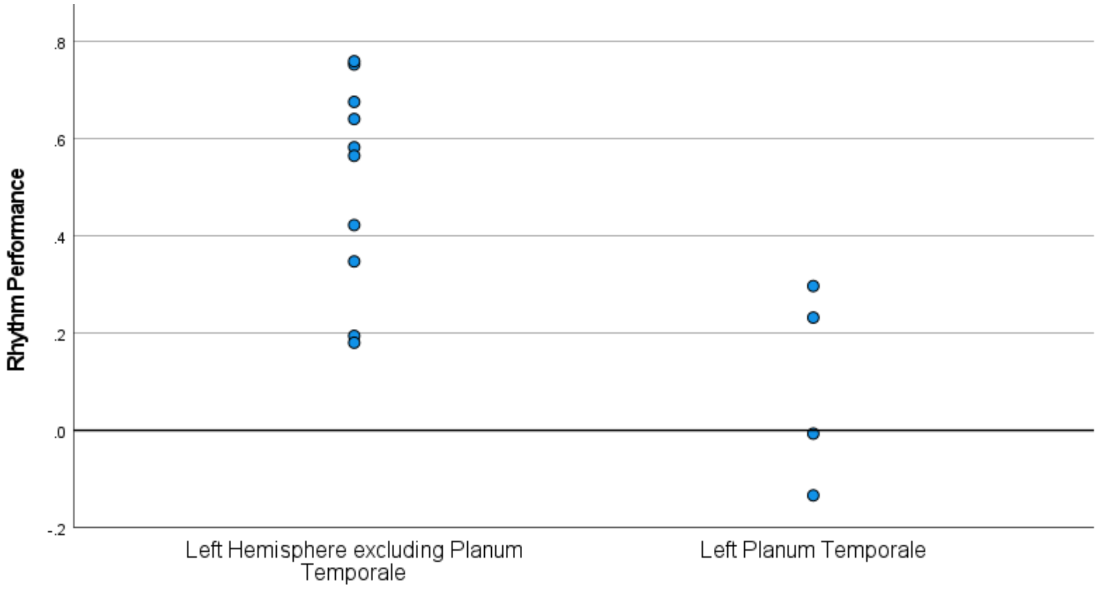


Figure 13

Production Error Scores for Participants With Left Planum Temporale and Other Left Hemisphere Lesion Sites

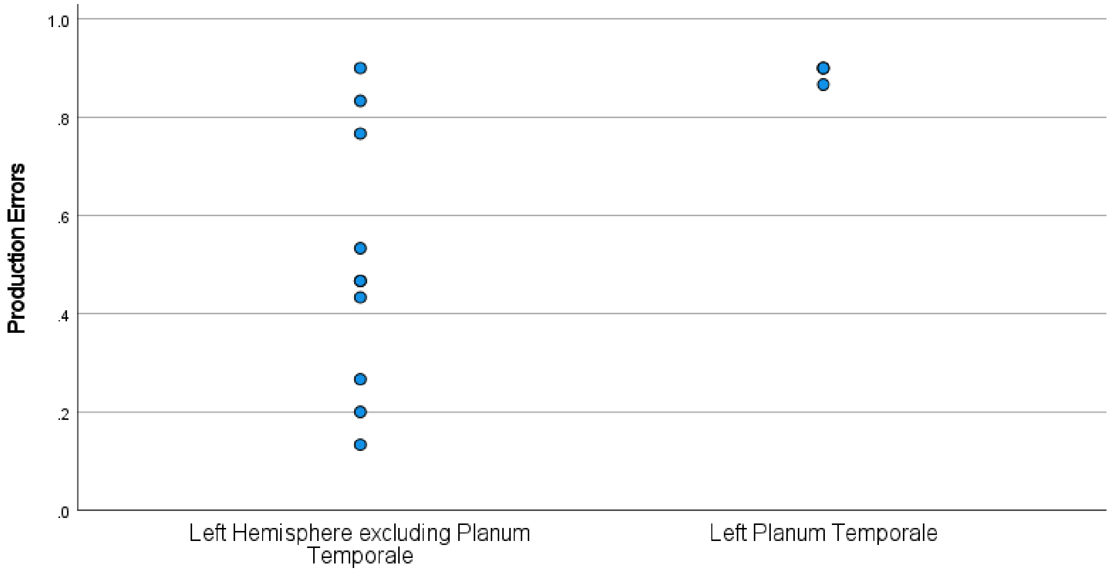


Figure 14

Melody Repetition Scores for Participants With Left Planum Temporale and Other Left Hemisphere Lesion Sites

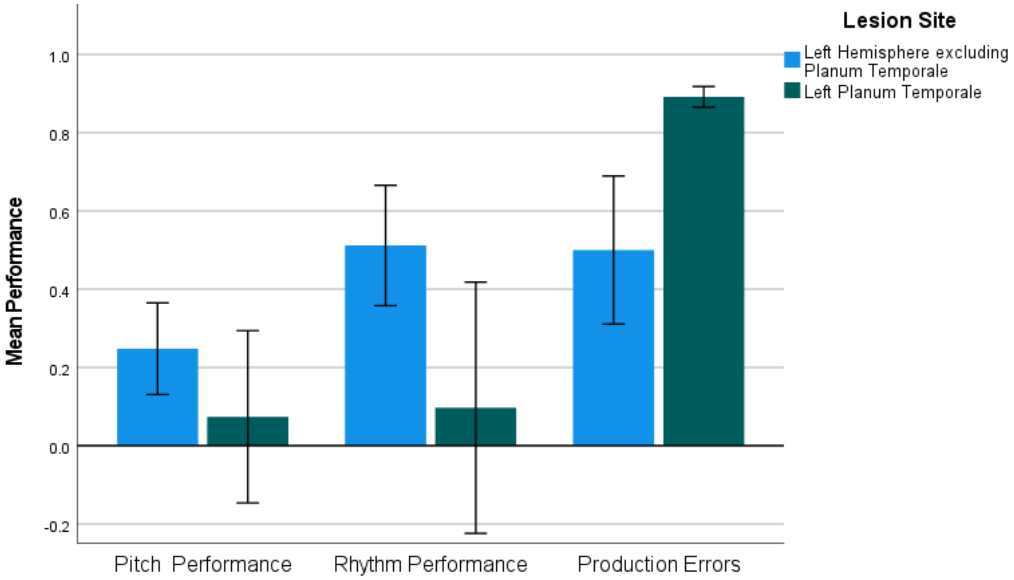
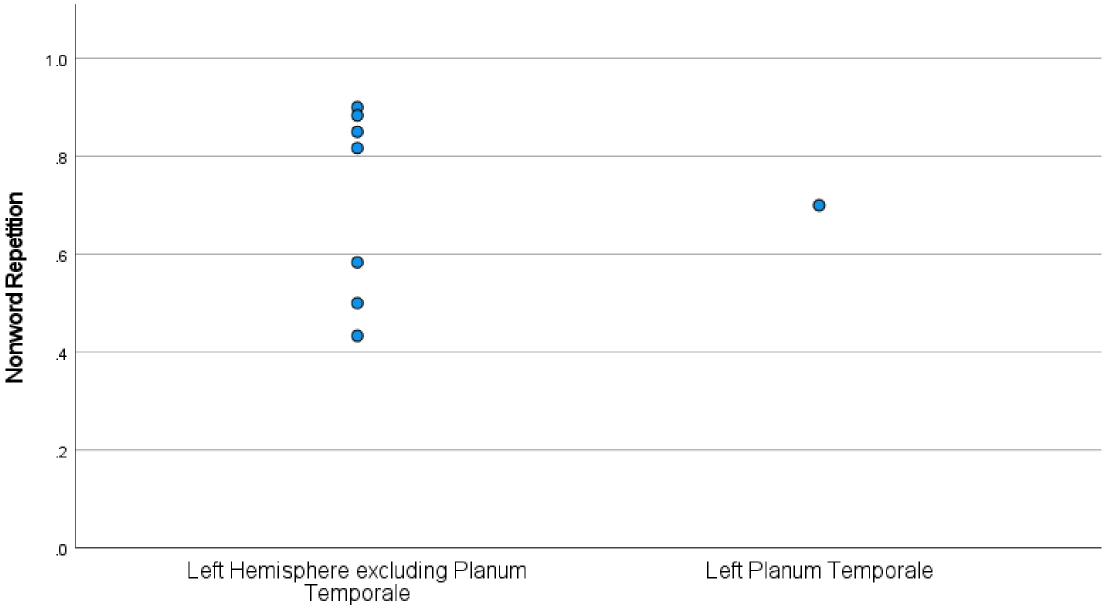


Figure 15

Nonword Repetition Scores for Participants With Left Planum Temporale and Other Left Hemisphere Lesion Sites

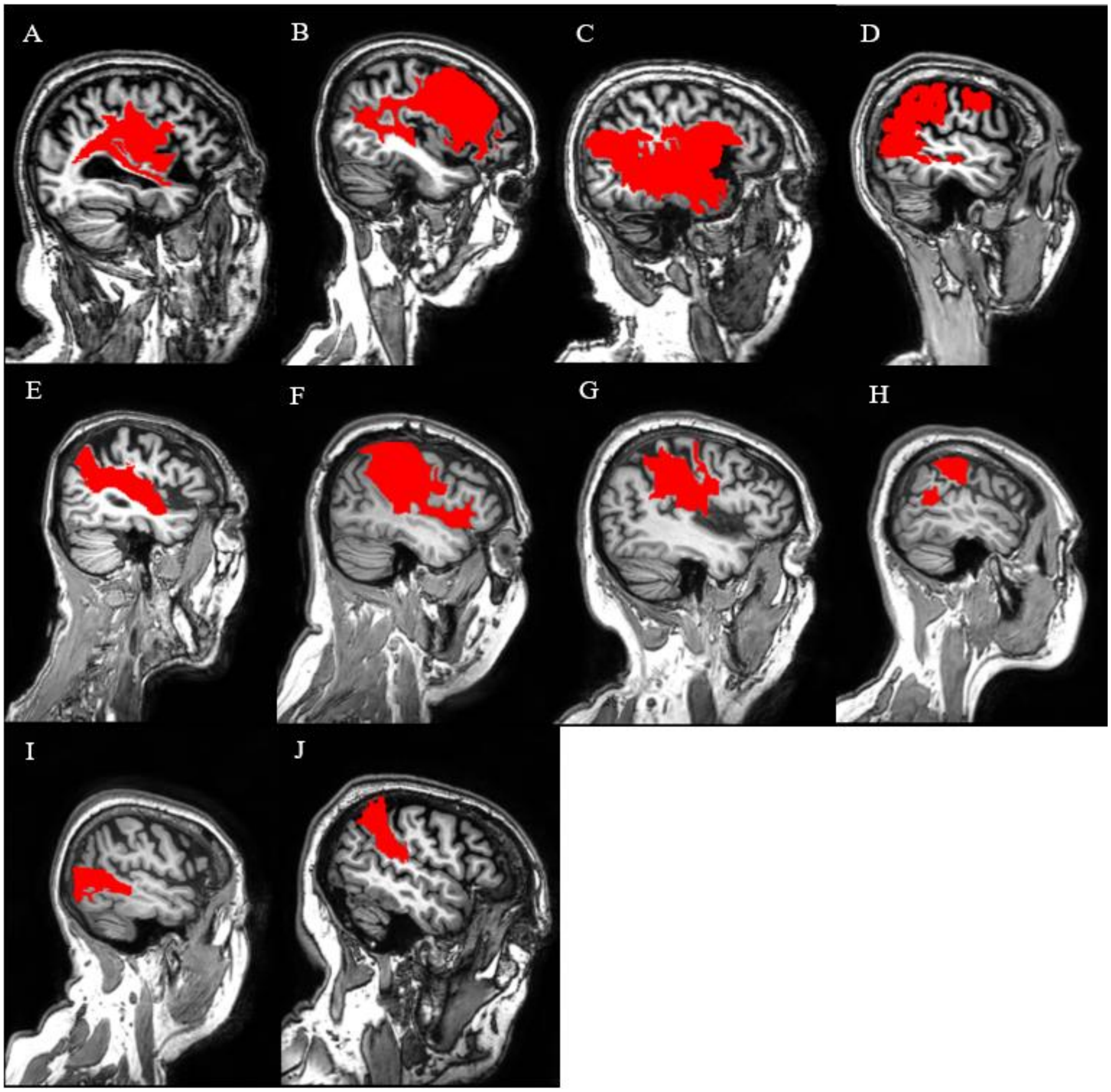


ROI-Based Analyses: Left Inferior Parietal Lobule

Next, to test the hypothesis that lesions in the left inferior parietal lobule will result in lower rhythm performance, we conducted Bayesian single-case *t*-tests between participants whose lesions include damage in the left inferior parietal lobule and those participants with left hemisphere lesions excluding the inferior parietal lobule. The results were as follows: of the 10 participants with lesions in the left inferior parietal lobule, 7 had poorer rhythm performance than those with lesions in other left hemisphere locations (p = 0.003, 0.005, 0.01, 0.02, 0.03, and 0.04) (Table 9 and Figure 18). There was also one participant, AZ1016 with a lesion in the left inferior parietal lobule that had a significantly higher pitch score (p = 0.02) and one, AZ1029, with a significantly lower score (p = 0.05) than those with left hemisphere lesions excluding the inferior parietal lobule (Table 9, Figure 17). Six of the participants with inferior parietal lobule lesions also made significantly more production errors compared to participants with lesions in other left hemisphere regions (p = 0.05 and 0.04) (Table 9, Figure 19).

Figure 16

Images of Lesion Locations of Participants With Lesions Including Left Inferior Parietal Lobule



Note: A) Participant AZ1006 B) Participant AZ1008 C) Participant AZ1012 D) Participant AZ1016 E) Participant AZ1028 F) Participant AZ1029 G) Participant AZ1030 H) Participant AZ1032 I) Participant AZ1034 J) Participant AZ1045

Table 9

Bayesian T-Test Single-Case Comparisons of Melody Repetition Performance for Left Inferior Parietal Lobule Versus Other Left Hemisphere Lesion Sites

	Pitch Performance		Rhythm Performance		Production Errors	
Participant	One-tailed *p*	%	One-tailed *p*	%	One-tailed *p*	%
AZ1006	0.15	14.80	**0.02**	**1.76**	**0.04**	**95.66**
AZ1008	0.45	44.57	**0.01**	**1.42**	**0.04**	**96.23**
AZ1012	0.46	50.00	**0.005**	**0.54**	**0.04**	**96.23**
AZ1016	**0.02**	**97.58**	0.42	42.35	0.26	25.95
AZ1028	0.41	41.20	**0.003**	**0.33**	**0.04**	**96.23**
AZ1029	**0.05**	**4.59**	**0.03**	**2.65**	**0.04**	**96.23**
AZ1030	0.34	66.02	**0.04**	**3.74**	0.36	64.34
AZ1032	0.13	13.39	**0.01**	**1.32**	**0.05**	**94.98**
AZ1034	0.40	60.23	0.07	6.64	0.07	93.22
AZ1045	0.18	81.95	0.47	53.12	0.30	69.55

Note. Results of the single-case Bayesian t-tests for melody repetition task. Percentages indicate a point estimate of the percentage of the control population that exhibits a lower nonword repetition score than the aphasia participant. Bold indicates statistical significance at p < .05.

Figure 17

Pitch Performance Scores for Participants With Left Inferior Parietal Lobule and Other Left Hemisphere Lesion Sites

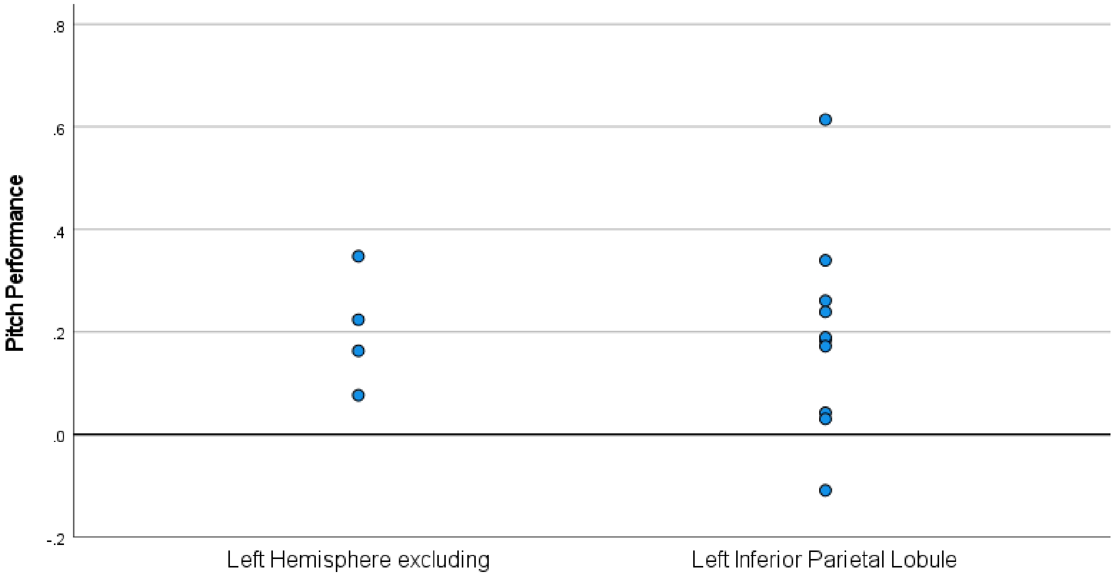


Figure 18

Rhythm Performance Scores for Participants With Left Inferior Parietal Lobule and Other Left Hemisphere Lesion Sites

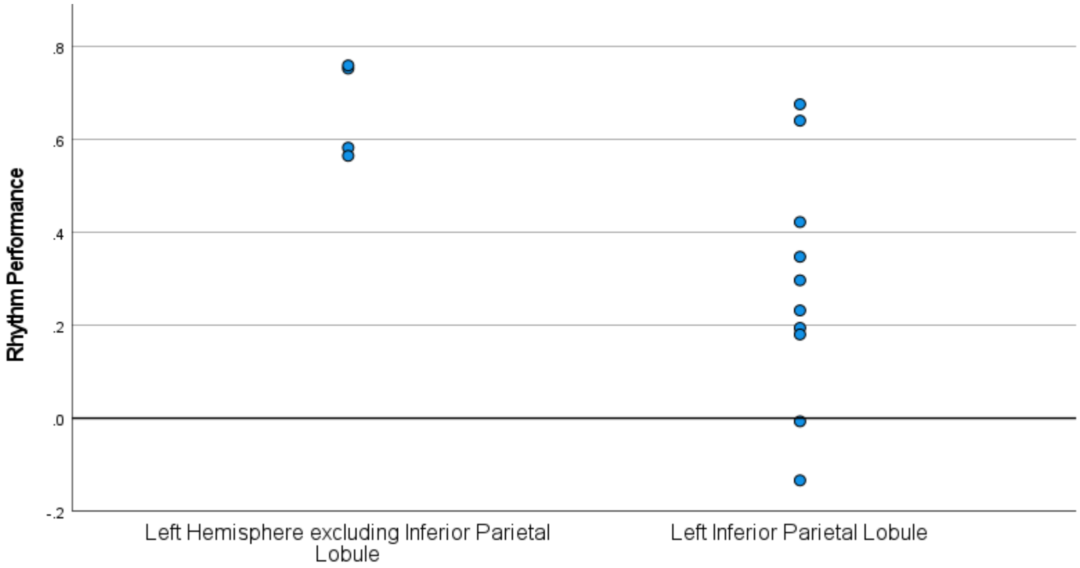


Figure 19

Production Errors for Participants With Left Inferior Parietal Lobule and Other Left Hemisphere Lesion Sites

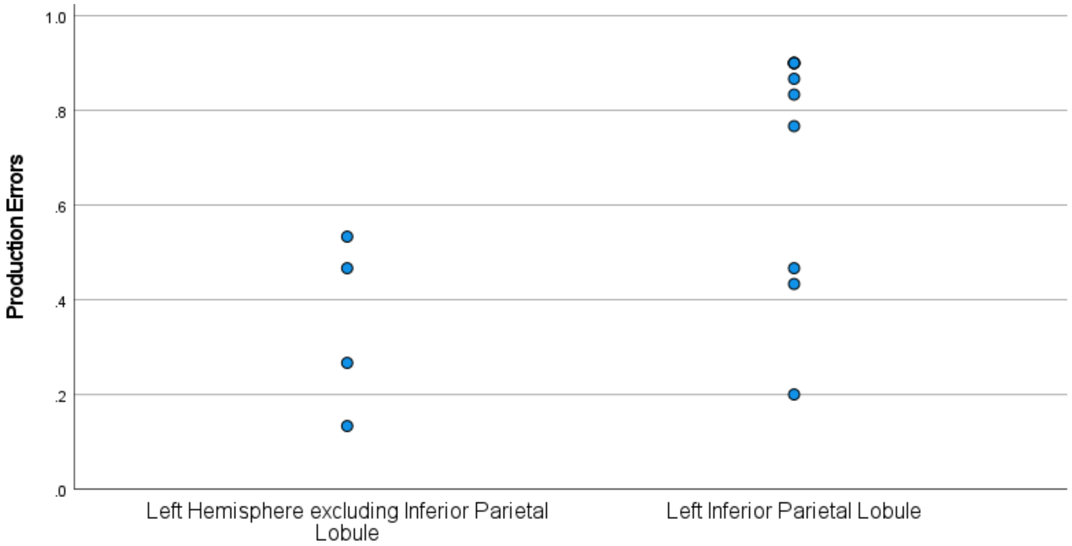
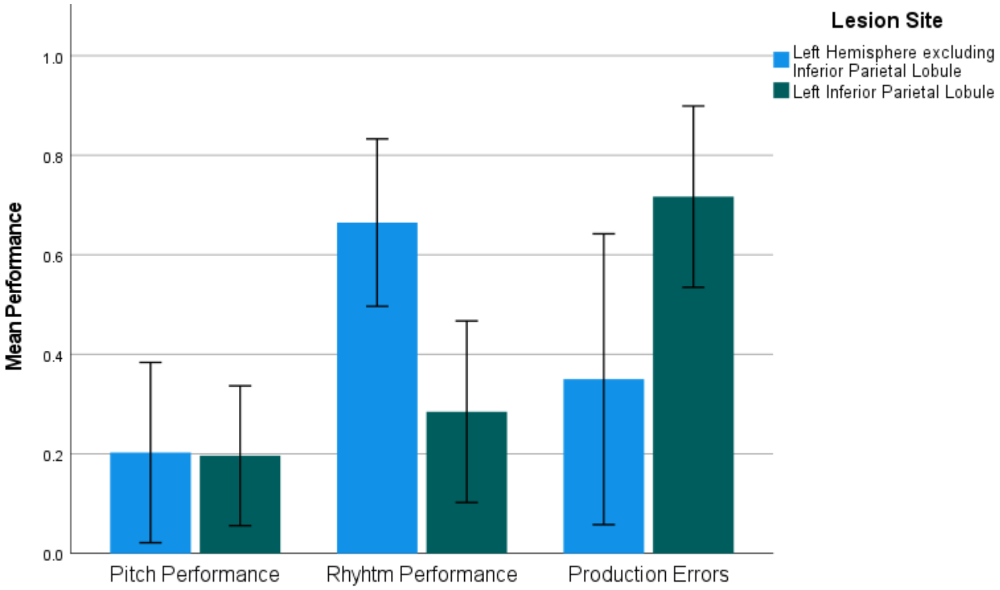


Figure 20

Melody Repetition Scores for Participants With Left Inferior Parietal Lobule and Other Left Hemisphere Lesion Sites

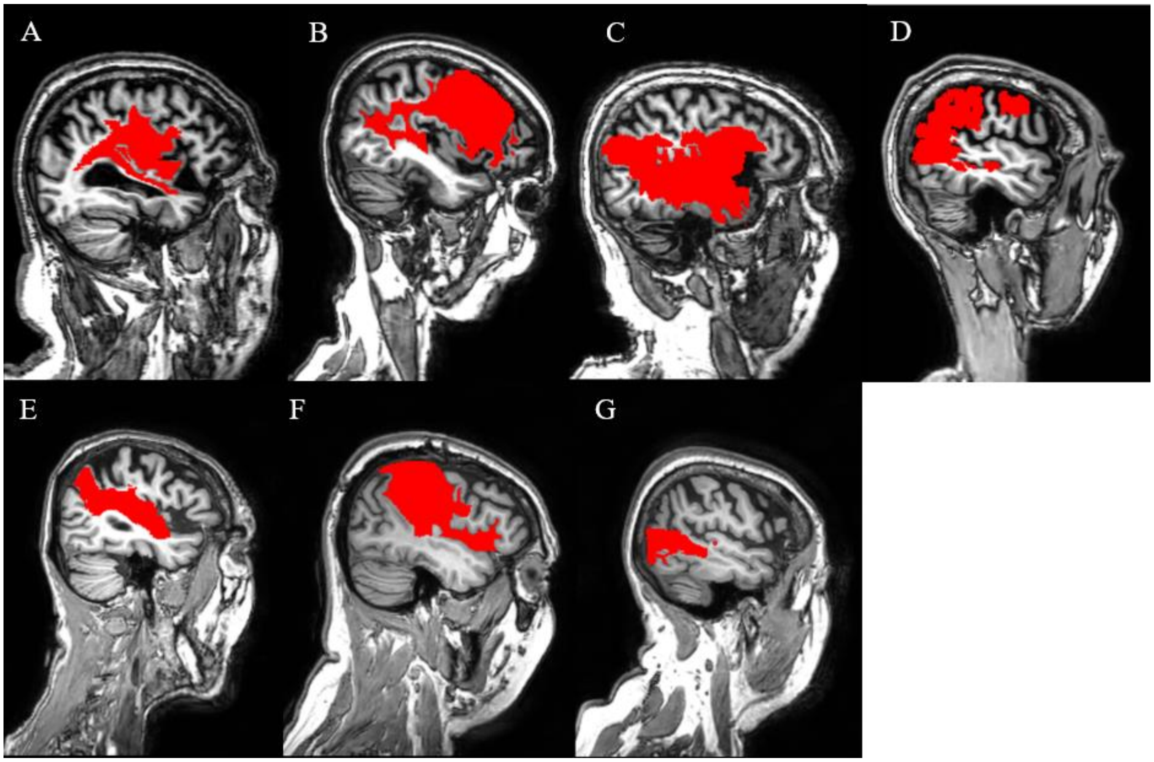


ROI-Based Analyses: Left Superior Temporal Gyrus (STG)

To test the hypothesis that large left superior temporal gyrus lesions will result in poorer performance across all three melody repetition measures, single-case Bayesian *t*-tests were conducted for the two participants with lesions encompassing both anterior and posterior portions of the STG, compared to the participants with left hemisphere lesions excluding both portions of the STG. Results indicate that all three participants with STG damage did not perform significantly differently than the participants with other left hemisphere lesions on pitch ($p = 0.20$, 0.45, and 0.42) or production errors ($p = 0.14$, 0.14, and 0.13) (Table 10, Figures 22 and 24). However, two of three participants with STG damage, AZ1012 and AZ1028, performed significantly worse than the other left hemisphere lesion participants on the rhythm measure ($p = 0.02$ and 0.01) (Table 10, Figure 23).

Figure 21

Images of Lesion Locations of Participants With Lesions Including Left Superior Temporal Gyrus



Note: A) Participant AZ1006 B) Participant AZ1008 C) Participant AZ1012 D) Participant AZ1016 E) Participant AZ1028 F) Participant AZ1029 G) Participant AZ1034 H) Participant AZ1045

Table 10

Bayesian T-Test Single-Case Comparisons of Melody Repetition Performance for Left STG Versus Other Left Hemisphere Lesion Sites

	Pitch Performance		Rhythm Performance		Production Errors	
Participant	One-tailed *p*	%	One-tailed *p*	%	One-tailed *p*	%
AZ1006	0.20	20.08	0.14	13.60	0.14	85.95
AZ1012	0.45	44.90	**0.02**	**2.48**	0.12	88.07
AZ1028	0.42	41.61	**0.01**	**0.94**	0.12	88.07

Note. Results of the single-case Bayesian t-tests for melody repetition task. Percentages indicate a point estimate of the percentage of the control population that exhibits a lower nonword repetition score than the aphasia participant. Bold indicates statistical significance at p < .05.

Figure 22

Pitch Performance Scores for Participants With Left aSTG and pSTG and Other Left Hemisphere Lesion Sites

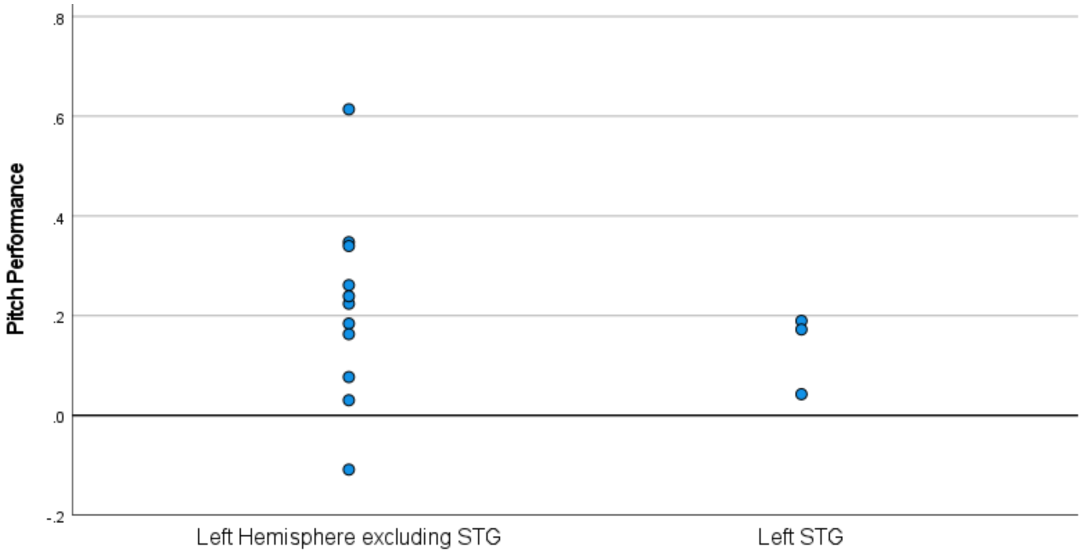


Figure 23

Rhythm Performance Scores for Participants With Left aSTG and pSTG and Other Left Hemisphere Lesion Sites

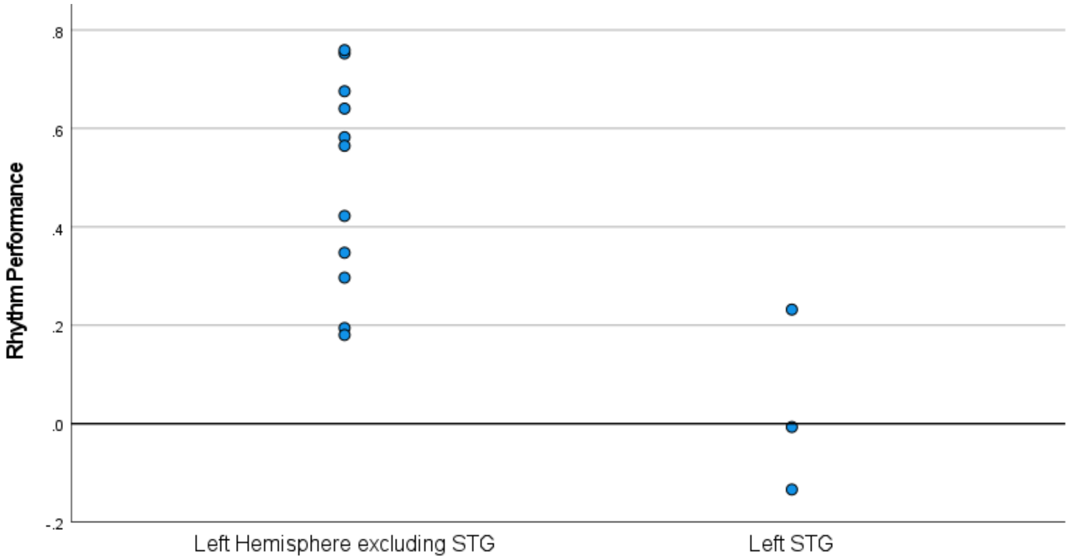
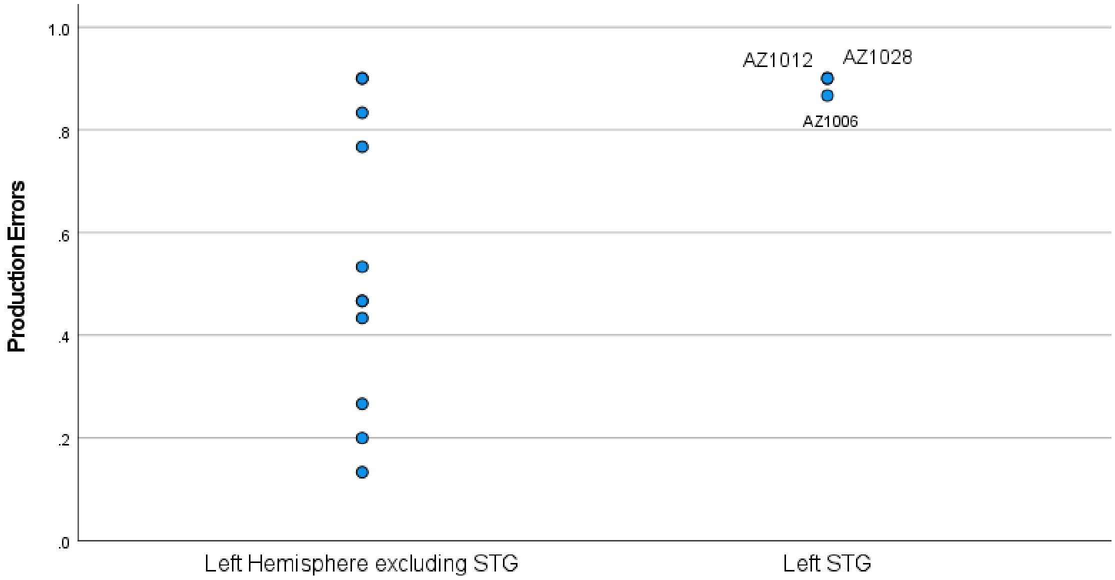


Figure 24

Production Error Scores for Participants With Left aSTG and pSTG and Other Left Hemisphere Lesion Sites



ROI-Based Analyses: Left Anterior Superior Temporal Gyrus (aSTG)

To test the hypothesis that the anterior portion of the left superior temporal gyrus is particularly critical for rhythm, Bayesian *t*-tests for each participant with anterior STG damage (n=3) were computed in comparison to participants with other left hemisphere lesion sites (n =11). Two of the three participants with anterior superior temporal gyrus damage participants AZ1012 (*p* = 0.02) and AZ1028 (*p* = 0.009) had significantly poorer rhythm performance than the participants with other left hemisphere lesion sites (Table 11, Figure 25).

Table 11

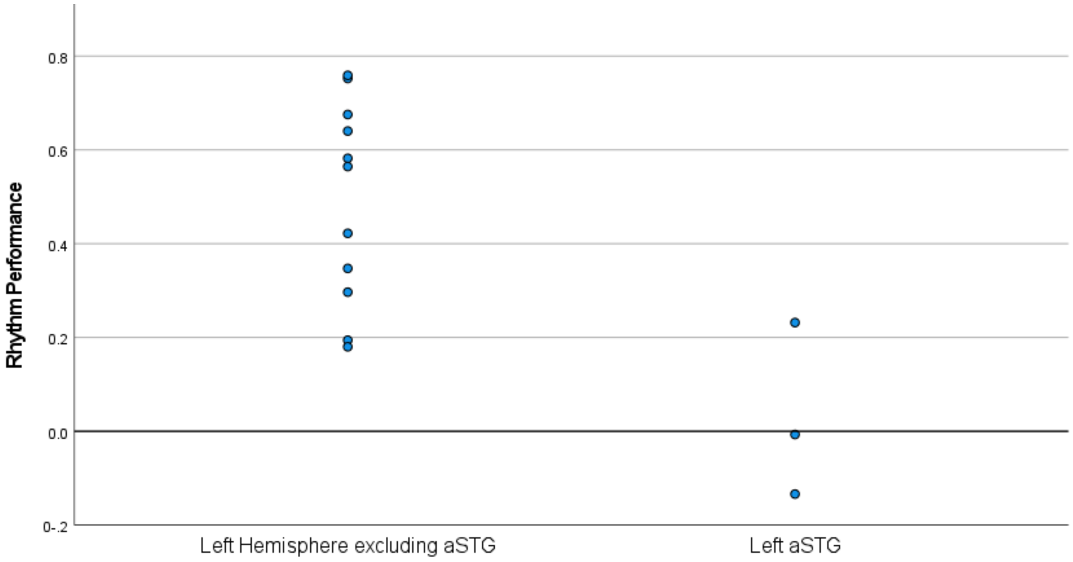
Bayesian T-test Single-Case Comparisons of Rhythm Performance for Left aSTG and Other Left Hemisphere Lesion Sites

Participant	One-tailed *p*	Percent of Control Population Below
AZ1006	0.14	13.59%
AZ1012	**0.02**	**2.49%**
AZ1028	**0.009**	**0.94%**

Note. Results of the single-case Bayesian t-tests for rhythm performance. Percentages indicate a point estimate of the percentage of the control population that exhibits a lower nonword repetition score than the aphasia participant. Bold indicates statistical significance at p < .05.

Figure 25

Rhythm Performance of Participants With Left aSTG and Other Left Hemisphere Lesion Sites



ROI-Based Analyses: Left Posterior Superior Temporal Gyrus (pSTG)

To test the hypothesis that the posterior portion of the STG (pSTG) is critical for pitch performance, we examined the performance of participants with damage to pSTG (n=7), to the performance of those with other left hemisphere lesion locations (n=7). There was a wide spread of scores on pitch performance for participants with lesions in the left pSTG as seen in Figure 26. A *t*-test comparing pitch scores of the participants with pSTG lesions versus other left hemisphere locations was not significant *t*(9.38) = 1.64, *p* = .44 (Table 12).

Table 12

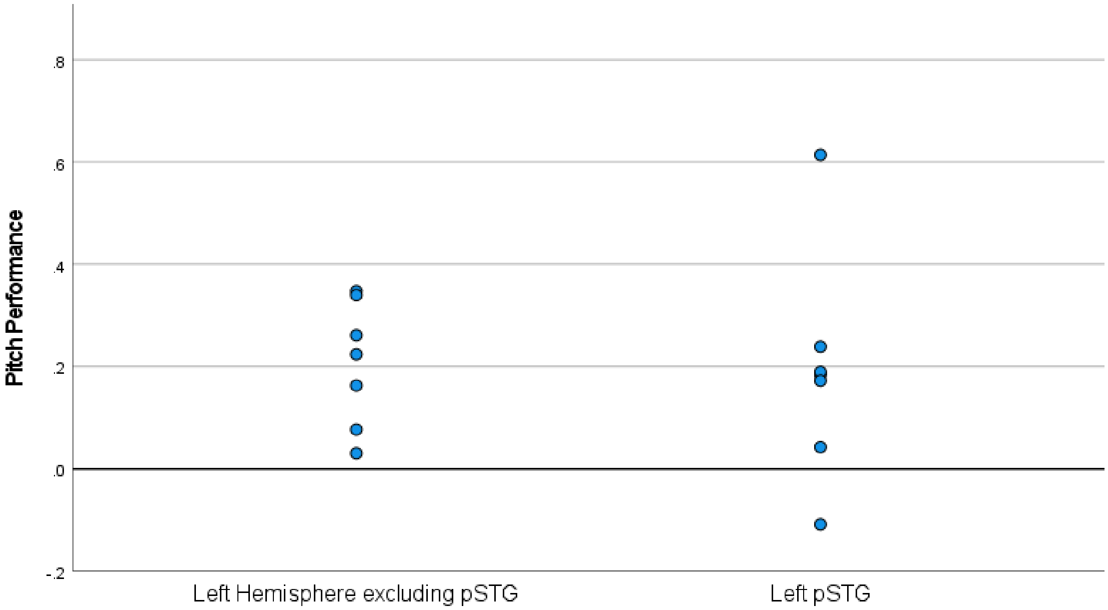
Differences Between Left Hemisphere and Left pSTG Participant Pitch Scores

	Left Hemisphere		Left pSTG					
	M	*SD*	*M*	*SD*	*df*	*t*	*p*	Cohen's *d*
Pitch Performance	0.21	0.12	0.19	0.22	9.38	1.64	0.44	0.18

Note: Welch's independent samples t-test statistics are reported as homogeneity of variance assumption was not met.

Figure 26

Pitch Performance Scores for Participants With Left pSTG and Other Left Hemisphere Lesion Sites

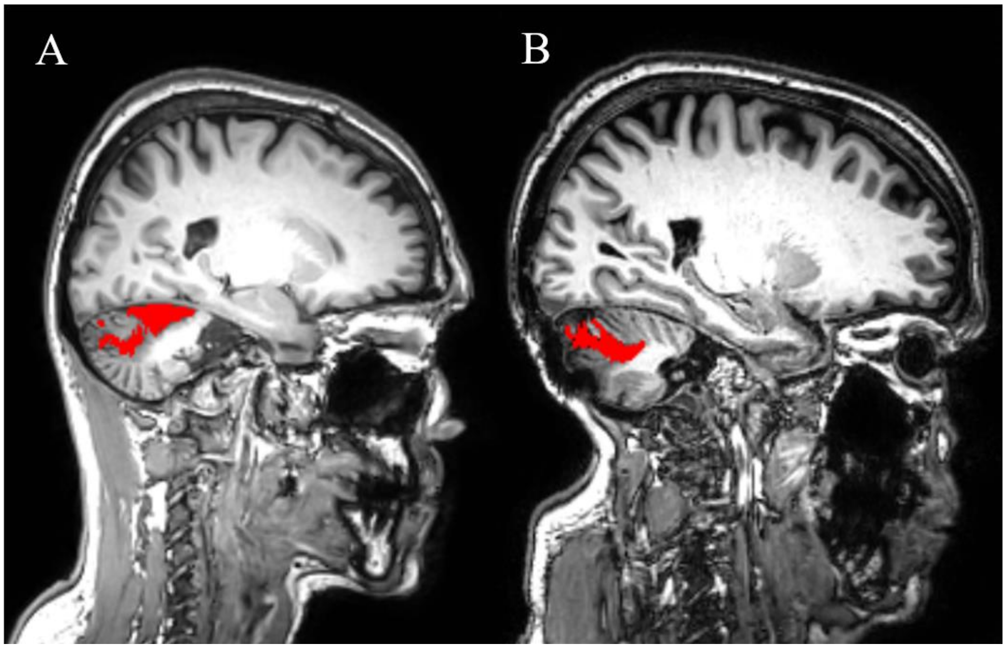


ROI-Based Analyses: Right Cerebellum

To test our hypothesis that the right cerebellum is involved in pitch and rhythm processing, we examined pitch and rhythm performance of individuals with lesions in the right cerebellum and the left hemisphere. To compare pitch and rhythm scores between participants with lesions in the right cerebellum (n=2) (Figure 27) to those in the left (cerebral) hemisphere (n = 14), we conducted single-case Bayesian *t*-tests. Results from these comparisons are summarized in Table 13. Results indicate that pitch performance for AZ1044 was significantly higher ($p = 0.03$) than the left hemisphere participants, and the other participant with cerebellar damage (AZ1024) trended in the same direction, though lacking significance ($p = 0.09$) (Figure 28). Rhythm performance was not significantly different for either participant with cerebellar damage (*p* = and 0.07) compared to participants with lesions in the left cerebral hemisphere. (Table 13, Figure 29).

Figure 27

Images of Lesion Locations of Participants With Lesions Including Right Cerebellum



Note: A) Participant AZ1024 B) Participant AZ1044

Table 13

Bayesian T-test Single-Case Comparisons of Rhythm Performance of Right Cerebellum and Left Hemisphere Lesion Sites

	Pitch Performance		Rhythm Performance	
Participant	*p*	%	*p*	%
AZ1024	0.09	91.29	0.21	78.87
AZ1044	**0.03**	**97.27**	0.07	92.77

Note. Results of the single-case Bayesian t-tests for pitch and rhythm performance. Percentages indicate a point estimate of the percentage of the control population that exhibits a lower nonword repetition score than the aphasia participant. Bold indicates statistical significance at p< .05.

Figure 28

Pitch Performance of Participants With Right Cerebellar and Left Hemisphere Lesion Sites

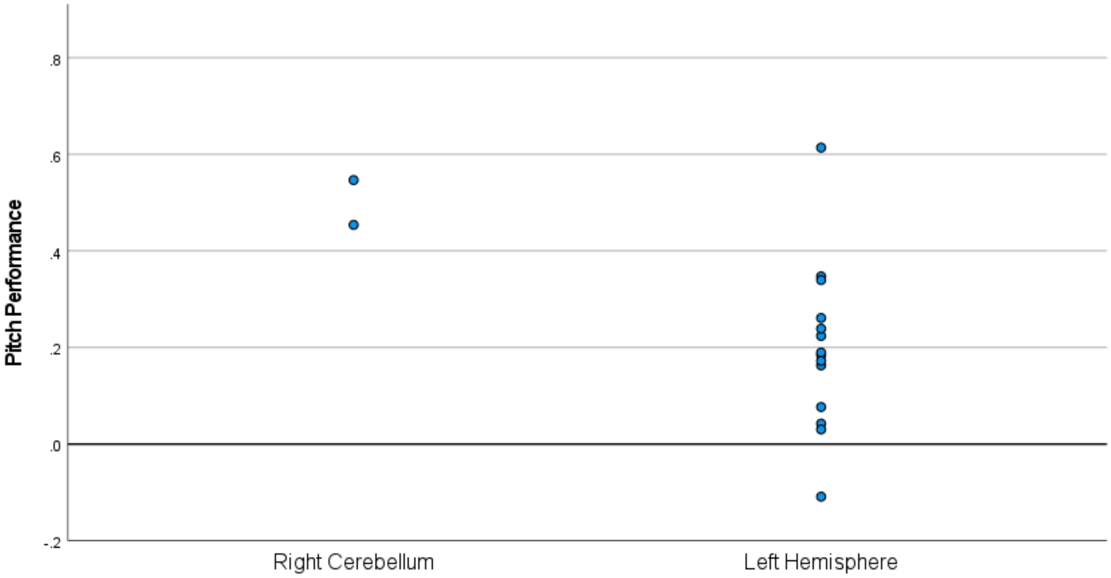
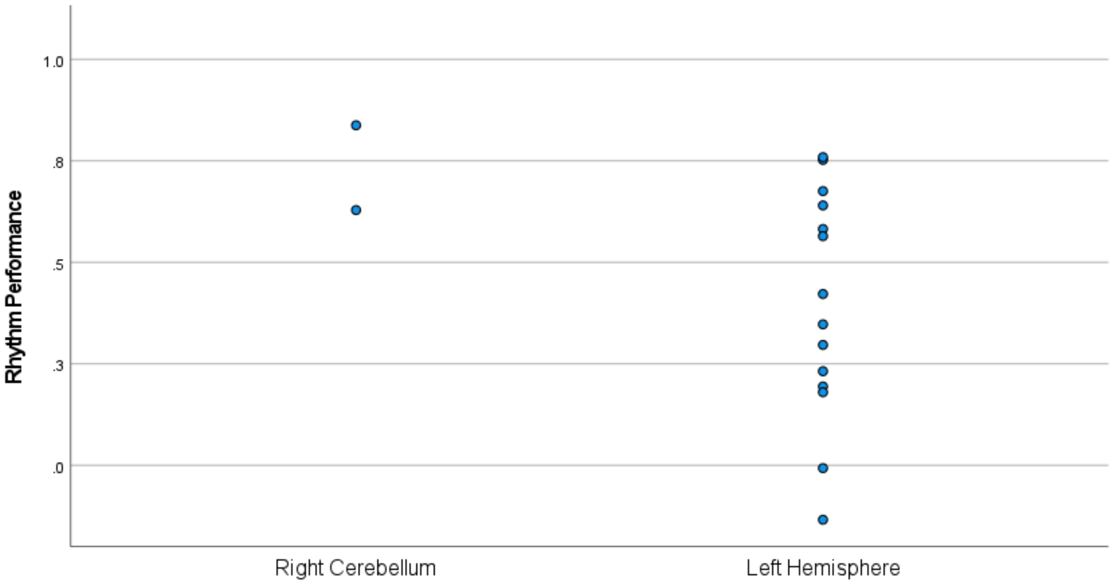


Figure 29

Rhythm Performance of Participants With Right Cerebellar and Left Hemisphere Lesion Sites



CHAPTER 4

DISCUSSION

The current study aims to inform our present understanding of music deficits in individuals with post-stroke aphasia using a melody repetition task similar to commonly used repetition tasks for speech. To this end, 27 individuals with chronic stroke were examined using both structural MRI and a behavioral battery, including a melody repetition task. We found that participants with aphasia and left hemisphere stroke exhibited a wide variety of performance on a melody repetition task, which we can quantify in an objective way in multiple dimensions: pitch, rhythm, and production errors. Overall, participants had lower scores in the pitch domain than the rhythm domain, but performance across these domains was significantly correlated. Nonword repetition was significantly correlated with pitch performance, but not rhythm performance or production errors which may indicate some functional overlap of these tasks. Working memory performance was positively correlated with rhythm performance scores and negatively correlated with production errors, suggesting that rhythm production may rely on working memory capacity more than pitch production during the melody repetition task. Regions of interest-based analyses generally indicate that left Heschl’s gyrus is heavily involved in all domains of melody repetition, while the left planum temporale, left inferior parietal lobule and the left superior temporal gyrus may be more critical for rhythm repetition. Below, these findings are discussed in more detail.

Broca’s area

Broca’s area is known to be involved in both speech and music processing (Koelsch, 2011; Kunert et al., 2015; Zatorre et al., 2002). Previous work had indicated that Broca’s area processes the temporal structures of speech and can work in conjunction with its right hemisphere homolog to process musical stimuli (Koelsch, 2011; Kunert et al., 2015; Zatorre et al., 2002). Therefore, we hypothesized that lesions to Broca’s area would be associated with lower melody repetition scores, specifically lower rhythm performance. It was unexpected that participants with lesions in Broca’s area did not show significantly lower scores on any of the music repetition domains than the other participants with left hemisphere lesions. This null finding could be due to factors including the neural plasticity found in patients during stroke recovery, especially considering that the right hemisphere is more involved in music processing, this plasticity, even if minor, may improve performance (Hartwigsen & Saur, 2019).

Left Superior Temporal Lobe

Bilaterally, the superior temporal lobe is frequently implicated in a variety of speech and music tasks, particularly regarding phonological and pitch processing (Brown et al., 2006; Koelsch, 2011; LaCriox et al., 2015; Peretz & Zatorre, 2005). Thus, we investigated several regions of interest in the superior temporal lobe. Participants with lesions in Heschl’s gyrus - the location of the primary auditory cortex - exhibited lower scores on all three melody repetition scores (pitch, rhythm, and production errors), but there was no significant effect on nonword repetition scores. This converges with evidence that bilateral Heschl’s gyrus activation is associated with singing and melody processing (Agustus et al., 2018 & Özdemir et al., 2006), but diverges from findings from the speech literature that the left Heschl's gyrus is critical for phonological processing (Kim et al., 2019). However, the role of the nearby planum temporale was less clear: participants with damage to the planum temporale showed a wide range of pitch performance scores in the melody repetition task. Of the four participants with lesions in this area, one had a significantly higher and another had a significantly lower pitch performance score compared to participants with lesions in other regions in the left hemisphere. Rhythm performance for two of the four participants with planum temporale lesions was significantly lower than participants with lesions in other left hemisphere regions which coincides with evidence that the planum temporale is a "hub" of melody processing (Agustus et al., 2018 & Patterson et al., 2002). The lack of significance in the other subjects could be attributed to the left planum temporale's proposed role in speech-specific integration, suggesting that the planum temporale may exhibit more laterality than other regions included in analyses (Morillon et al., 2010).

The superior temporal gyrus itself has been well-studied regarding its role in speech and music processing (Abrams, et al., 2010; Gaab et al.,2003; Kim et al., 2019 LaCriox et al., 2015). The relative contributions of the anterior versus posterior portions of the superior temporal gyrus are particularly hotly debated (Evans et al., 2014). Both participants with lesion locations encompassing both the anterior and posterior sections of the STG had significantly lower rhythm performance than those with lesions elsewhere in the left hemisphere. This evidence is consistent with fMRI research showing the left STG to be involved in encoding rhythmic information in neurotypical adults (Konoike et al., 2012). Of the three participants with lesions in the left anterior STG, two scored significantly lower on rhythm performance which is in line with the theory that the anterior region of STG is more utilized in rhythm processing and the posterior in pitch processing (Sihvonen et al., 2020). Contradictory to our hypothesis, we did not see significantly lower scores on pitch performance for individuals with lesions in the posterior STG. Lesions in the adjacent left inferior parietal lobule were associated with significantly lower scores for rhythm performance, implying that this region may play a role in rhythm processing which also has been suggested by fMRI evidence (Konoike et al., 2012). Thus, although it was surprising that pitch performance did not track with STG damage, this could be attributed to the fact that many of the participants in our sample with anterior damage also exhibited posterior STG damage potentially leading to more severe rhythm deficits than pitch deficits.

Cerebellum

Our last region of interest was the right cerebellum. The right cerebellum, highly connected to the left-lateralized language network and motor network, has also been implicated in rhythm processing, music discrimination, music error detection, and music memory (Gaab et al., 2003; Konoike et al., 2012; LaCriox et al., 2015). But notably, one of the two participants with right cerebellar lesions had a significantly higher score on pitch performance than participants with lesion locations in the left hemisphere. While this was the only significant finding in this region, it is unlikely that this high score is due to a lack of cerebellar involvement in melody repetition - especially rhythm performance, as this region has been proposed in playing a role in encoding and retrieving rhythmic information and coordinating the timing of motor movements necessary in replicating rhythm (Abrams et al., 2011; Konoike et al, 2012). This participant did state that they were a long-time musician who plays guitar and sings, which was likely a confounding factor contributing to the significantly high score in pitch repetition. The null findings in the rest of our cerebellar analyses on melody repetition may be due to the relatively spared lobules V and VI implicated in pitch memory as well as potential compensation in the right hemisphere from plasticity following stoke (Gaab et al., 2003 & Hartwigsen & Saur, 2019).

Limitations and Future Directions

While the current study provides preliminary evidence for specific melody repetition deficits in individuals with aphasia, there are limitations that should be considered. One limitation is that pitch tracking is difficult in healthy control subjects and becomes more difficult when working with individuals with stroke due to weak vocal qualities as a consequence of stroke. The task design may have been uncomfortable for some participants as they were asked to sing in front of another person, which can make some feel embarrassed, especially when they are aware of their speaking deficits. Another limitation is the lack of data collected on previous musical training. Since musical training is often found to be a correlate of auditory processing of both modalities (Kolesch, 2011 & Peretz & Zatorre, 2005), future studies should examine the relationship between musical training and the reliance on different auditory processing regions for pitch and rhythm replication post-stroke.

Future research should aim to collect data not only from the melody repetition task but also from music perception tasks, such as from the Montreal Battery Evaluation of Amusia (MBEA) (Peretz et al., 2003). Utilizing both sensory and sensorimotor tasks would aid in gaining a detailed understanding of an individual's deficits, be they issues with perception, working memory, and/or production. It should be noted that the MBEA does have increased cognitive demand which can limit its application in some participants (Peretz et al., 2003). It is also important to include a larger sample size in future analyses as many of our analyses were on an individual basis due to a lack of statistical power.

Conclusion

Our findings indicate that, overall, rhythm performance and production errors were correlated with working memory performance. Performance in the pitch and rhythm domains were also correlated. These domains are parsed when analyzing individual regions of interest, however. The left Heschl’s gyrus was seen to be the most involved in all domains of melody repetition, pitch, rhythm, and production errors. Several of our regions of interest were also involved in melody repetition, specifically in the rhythm domain, including the left planum temporale, left inferior parietal lobule, and left superior temporal gyrus. Pitch performance was highly variable in participants with left inferior parietal lobule lesions and right cerebellar lesions. The left inferior parietal lobule was also seen to be related to higher levels of production errors on the melody repetition task. While these findings are preliminary, they do suggest further research into the often-understudied musical deficits in individuals struggling with aphasia. By assessing both modalities, clinicians can gain better insight into the specific cognitive profile of an individual which can help to guide treatment plans.

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