The Neuroanatomy of Speech Processing: A Large-Scale Lesion Study

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Running Title: Neuroanatomy of Speech Processing

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Abstract

The neural basis of language has been studied for centuries, yet the networks critically involved in simply identifying or understanding a spoken word remain elusive. Several functional-anatomical models of the critical neural substrates of receptive speech processes have been proposed, including auditory-related regions in the (1) left *mid-posterior* superior temporal lobe, (2) left *anterior* superior temporal lobe, or (3) *bilateral* in the mid-posterior superior temporal areas, and (4) *motor*-related regions in the left frontal lobe (in normal and/or noisy conditions). One difficulty in comparing these models is that they often focus on different aspects of the sound-to-meaning pathway and different types of stimuli and tasks. Two auditory tasks that are typically used in separate studies—nonword discrimination and word comprehension—often yield different conclusions. We assessed word/nonword discrimination and clear/noisy word comprehension in 160 individuals with focal brain damage: left (n=115) or right (n=19) hemisphere stroke, left (n=18) or right (n=8) anterior temporal lobectomy, and 26 neurologically-intact controls. Discrimination and comprehension doubly dissociated both behaviorally and neurologically. In support of a bilateral model, clear speech comprehension was near ceiling in 92% of left stroke cases, and right temporal damage was, for the first time, found to impair phoneme discrimination. Lesion-symptom mapping analyses for the word discrimination, non-word discrimination, and noisy word comprehension tasks each implicated most of the left superior temporal gyrus (STG) except the anterior most regions. Comprehension tasks also implicated the left pMTG, while discrimination tasks also implicated more dorsal sensorimotor regions in posterior perisylvian cortex.

In 1874, Carl Wernicke (Wernicke, 1874) proposed that the left superior temporal lobe serves as the substrate for what we today generally call speech perception, the processes up to and including the successful activation of a phonological word form. The proposal is intuitively appealing in that the region is in auditory-related cortex and in the language dominant hemisphere. But the claim has been challenged from several angles, leading to at least three current competitors to Wernicke's hypothesis. The first, based mostly on studies of phoneme perception using tasks such as syllable discrimination, challenges the view that sensory cortex alone is sufficient for perceptual processes, as these tasks invoke motor cortex involvement (Pullvermuller *et al.* 2005, 2006; Rizzolatti & Arbib, 1998; Watkins *et al.* 2003; Wilson *et al.* 2004). This view was first proposed in the form of the motor theory of speech perception (Liberman, 1957, 1967) and indirectly linked the process to motor cortex. It was subsequently challenged by several examples of normal speech perception ability in the face of impaired or non-existence motor speech ability (Eimas *et al.* 1971; Kuhl & Miller, 1975; Bishop *et al.* 1990), but this claim was revived with the discovery of mirror neurons in macaque monkeys (Gallese *et al.* 1996). Consistent with this motor centric view of speech perception, modern neuroimaging studies have shown that motor speech regions indeed activate during listening to phonemes and syllables (Pulvermuller *et al.* 2006; Wilson *et al.* 2004; Buchsbaum *et al.* 2001; Hickok *et al.* 2003), but strong versions of motor centrism remain improbable for reasons given above (Hickok, 2014). A more moderate proposal in this vein is that the motor system augments speech perception only under noisy listening conditions (Wilson, 2009).

A second challenge to Wernicke's model came from neuroimaging studies at the beginning of this century showing a left dominant and specifically *anterior* superior temporal region that appeared to respond selectively to intelligible speech (Scott *et al.* 2000). Although this anterior superior temporal region has been proposed to be critical for "speech-specific processing" more broadly, the stimuli in these studies have typically been sentences (Scott *et al.* 2000; Evans *et al*. 2014; Narain *et al.* 2003), raising the possibility that the activation in these regions is at a later stage of processing (Rogalsky et al. 2011a; Brennan & Pylkkanen, 2012).

Finally, a third challenge came from the study of people with language disorders (aphasia) following acquired brain injury: it was found that left hemisphere damage generally produced only mild deficits in the ability (as measured by word to picture matching tasks), whereas bilateral superior temporal lesions could produce profound deficits even when pure tone hearing thresholds are normal, i.e., "word deafness" (Buchman et al. 1986; Miceli et al. 1980; Poeppel, 2001; Henschen, 1926). In addition, studies of the isolated right hemisphere in callosotomy patients found that the right hemisphere exhibited good comprehension of most auditory words and simple phrases (speech was presented to both ears and the hemisphere isolated by only allowing responses to be made with one or the other hand; Zaidel, 1985; Gazzaniga & Sperry, 1967). These findings led to the proposal that speech perception can be mediated in the superior mid to posterior temporal lobes *bilaterally* (Gazzaniga & Sperry, 1967; Buchman et al. 1986; Zaidel, 1985; Bachman & Albert, 1988; Goodglass, 1993; Hickok & Poeppel 2000, 2004, 2007) which would explain the substantial effects of bilateral damage, while individuals with unilateral damage (to either hemisphere) typically are unimpaired on auditory word comprehension tasks.

Much of the modern research on this topic has been carried out using neuroimaging methods, which cannot assay the causal involvement of activated networks. There have been attempts to assess the competing proposals more directly using neuropsychological (Bak & Hodges, 2004) or neural interference methods (e.g., transcranial magnetic stimulation, TMS) (D'Ausilio *et al.* 2009; Meister *et al.* 2007; Mottonen & Watkins, 2009), but methodological concerns have rendered them equivocal (Hickok, 2014). Thus, despite more than a century of study, the neural basis of speech perception remains controversial. Here we present the first large scale lesion study of the ability to recognize and discriminate single words and syllables using a set of tightly controlled tasks and populations that can adjudicate between the dominant hypotheses.

We employed two auditory word comprehension tasks and two speech discrimination tasks. Both auditory word comprehension tasks involved matching a spoken word to a picture in an array of four where one picture was the target and the other three were phonological, semantic, and unrelated distractors. In one version of the task, speech was presented in a quiet background (clear speech), and in the other version, speech was presented in white noise. The speech-in-noise task was included for two reasons, first to mitigate the possibility of ceiling effects, and second, to allow an assessment of the claim that motor speech systems play a role in speech perception under noisy listening conditions.

The speech discrimination tasks involved the presentation of pairs of monosyllabic speech stimuli with minimally contrasting onsets and a 1 second inter-stimulus interval. The listener was asked to decide whether the two stimuli were the same or different. One version of the task involved real words and the other involved nonwords. Despite the intuitive assumption that both

discrimination and auditory word comprehension tasks measure an ability to extract sound-based phonological information from a speech signal, these two tasks are reported to be doubly-dissociable (Miceli et al. 1980; Hickok & Poeppel, 2004). Particularly paradoxical are cases in which the ability to discriminate pairs of syllables (e.g., *da* from *ba*) is impaired while the ability to differentiate words with these same sounds (e.g., *doll* versus *ball*) is spared in comprehension tasks. This has confounded models of the neural basis of speech perception and recognition for decades because one can reach different conclusions depending on which task is used (Hickok & Poeppel, 2000; Hickok, 2014). We sought to resolve this issue in the present study by employing both tasks in a large sample. We studied people with either left or right hemisphere chronic stroke, left or right anterior temporal lobectomy, and neurologically intact controls. For our largest group (left hemisphere stroke patients) we use lesion-behavior mapping to identify brain regions responsible for receptive speech deficits.

Methods

Participants

Consent from all participants (described below) was obtained according to the Declaration of Helsinki and the experiments were approved by the Institutional Review Boards of all the institutions at which the work was performed.

Lesion Participants. 115 left hemisphere stroke patients (Figure 1; 46 female, age range = 31-86, mean age = 61 years, years of education range = 8-20, mean education = 15 years, years

post-stroke range = 0.5-32, mean years post-stroke = 6.1) were tested at six institutions: University of Iowa (n=40), University of South Carolina (n=32), Medical College of Wisconsin (n=26), San Diego State University (n=9), Arizona State University (n=7) and University of California, Irvine (n=1). In addition, 19 right hemisphere stroke patients (6 female, age range = 25-75, mean age = 52 years, years of education range = 10-20, mean education = 15 years, years post-stroke range =0.5-35, mean years post-stroke = 11.0; Figure 2A, B), 18 patients who underwent a unilateral left temporal lobectomy (10 female, age range = 29-62, mean age = 48 years, years of education range = 10-16, mean education = 13.5 years, years post-lobectomy range =0.7-14, mean years post-lobectomy = 4), and 8 patients who underwent a unilateral right temporal lobectomy (5 female, age range = 23-60 mean, age = 41 years, years of education range = 12-18, mean education = 14 years, years post-lobectomy range =4-18, mean years post-lobectomy = 9) were tested (Figure 2 C,D). The right hemisphere stroke patients were tested at University of Iowa (n=17), University of South Carolina (n=1) and Arizona State University (n=1). All lobectomy patients were tested at the University of Iowa. Patients were included in the present study based on the following criteria: (i) a chronic focal (6 months or more post-onset) lesion due to a single stroke in either the left or right cerebral hemisphere or a unilateral temporal lobectomy (ii) no significant anatomical abnormalities other than the signature lesion of their vascular event (or evidence of surgery for the lobectomy subjects) nor signs of multiple strokes, (iii) an absence of a history of psychological or neurological disease other than stroke (or seizure disorder for the lobectomy subjects), (iv) native English speaker, (v) right handed pre-stroke, and (v) ability to follow task instructions. The temporal lobectomy patients all had a seizure disorder

that required lobectomy surgery for the treatment of their seizures[1]. All stroke participants had ischemic strokes, with the exception of two left hemisphere patients with hemorrhagic strokes.

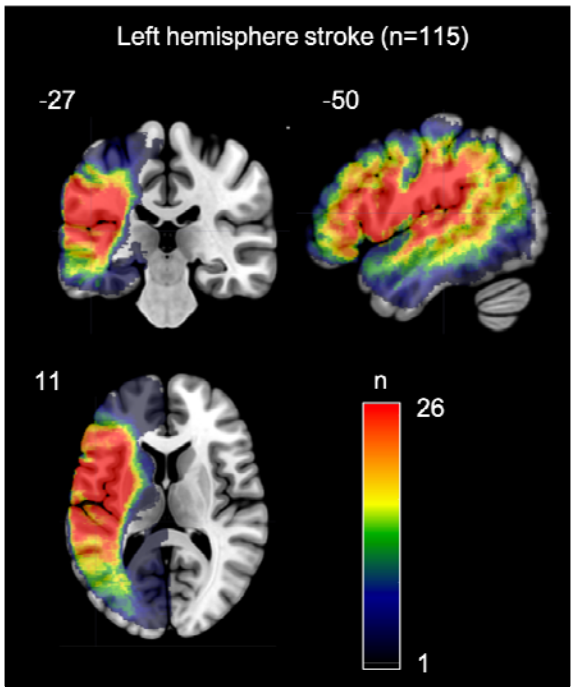

Figure 1. Overlap map of the areas of damage in the 115 participants with a left hemisphere stroke.

Given the proposed role of the right mid-posterior STG in speech perception, the right hemisphere stroke patients were divided into two groups: those with right mid-posterior STG damage (n=11; 11/11 lesions overlap in white matter of mid-posterior STG) and those with no mid-posterior STG damage (n=8; max overlap is 3/8 subjects in portions of the inferior frontal

[1] The participants with temporal lobectomies have lesions localized in the anterior temporal lobe (Fig S1), a region that is often left intact by all but the most severe middle cerebral artery strokes (Holland & Lambdon Ralph, 2010) and therefore of particular value to the present study. However, there is evidence that epileptic brains have variable functional organization, including laterality of speech processing *(*Swanson et al. 2002, 2007; Hertz-Pannier et al. 2002*)*. Thus, findings in this population should be interpreted carefully.

gyrus, precentral gyrus and insula) (Figure 2A,B). Mid-posterior STG was defined as any gray or white damage in the STG adjacent or posterior to Heschl's gyrus as determined by visual inspection by one of the authors (Rogalsky) with extensive training in cortical neuroanatomy.

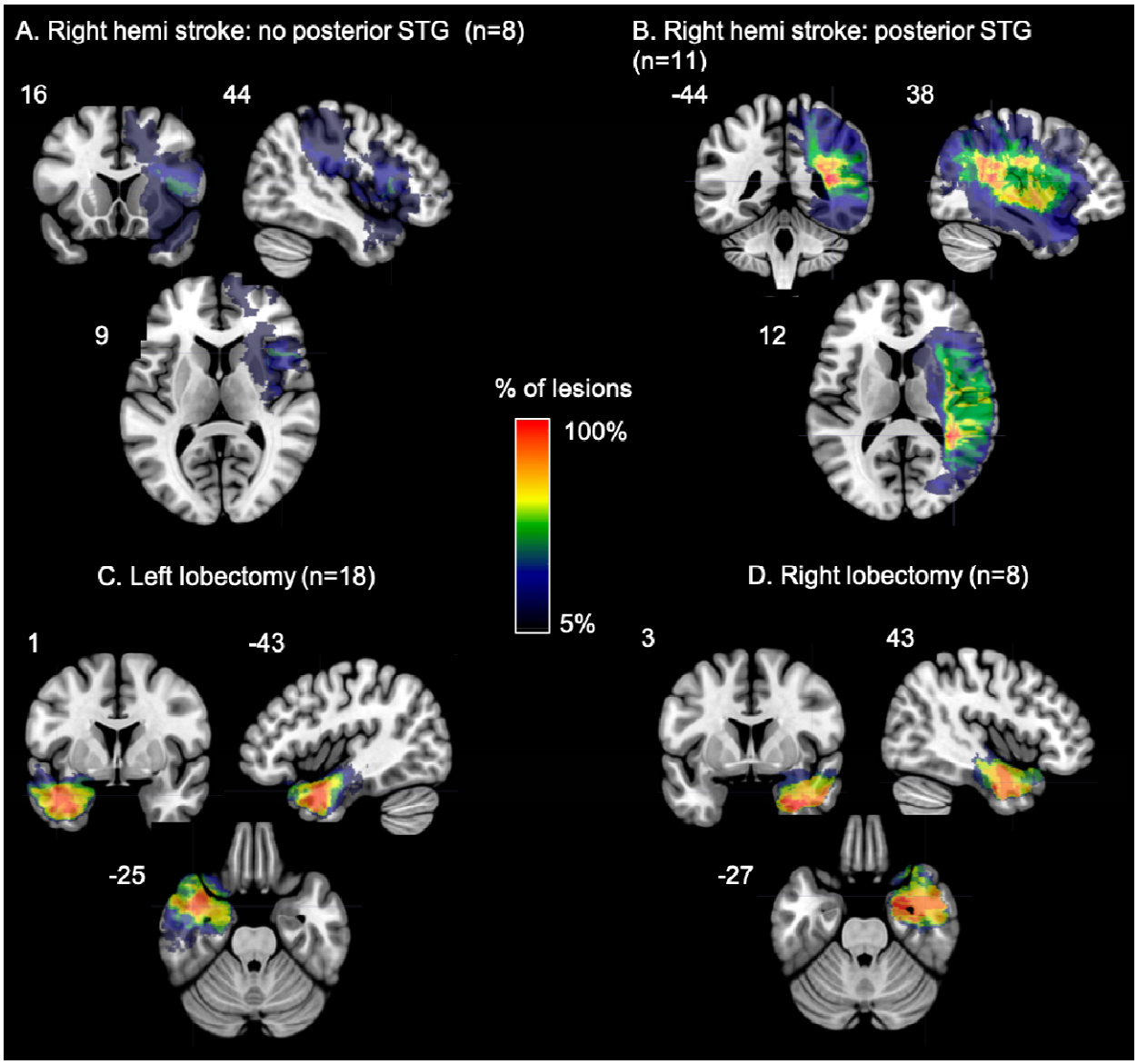

Figure 2. (A,B): Overlap map of the areas of damage in the participants with a right hemisphere stroke (A) without and (B) with STG damage. (C,D): Overlap map of the areas resected in the participants who underwent a (C) left or a (D) right temporal resection.

Control Subjects. Twenty-six adults (21 female, age range = 42-83, mean age = 59 years, years of education range = 12-16, mean education = 15 years) were recruited and tested at San Diego State University. All control subjects were native English speakers, right-handed, and self-reported no history of psychological or neurological disease.

Informed consent was obtained from each patient prior to participation in the study, and all procedures were approved by the Institutional Review Boards of UC Irvine, University of South Carolina, San Diego State University, Arizona State University, Medical College of Wisconsin and University of Iowa.

Materials

The present study focuses on two types of tasks: auditory word comprehension and speech discrimination. The tasks were administered as part of an extensive psycholinguistic test battery to assess receptive and productive speech abilities. Within the battery, individual tests themselves were presented in a non-fixed pseudorandom order. Items within a test were presented in a fixed random order at all testing sites, except for Medical College Wisconsin (n=26), where items were presented in a random order for each subject.

Auditory Comprehension Measures

Auditory word comprehension in a clear background. A four alternative forced choice word-to-picture matching task previously used by Rogalsky et al. (2011b) and similar to Baker, Blumstein, and Goodglass' (1981; Blumstein *et al.* 1977) paradigm was administered. The task contained 20 trials. In each trial an auditory word was presented one second after the appearance of a picture array depicting four objects on a computer screen. The words were recorded by a male native speaker of American English. The participant was instructed to point to the picture that matched the auditorily-presented word. The picture array contained the target and three distractors, one phonemic, one semantic, and one unrelated. Ten of the 20 trials contained a phonemic foil that represented a minimal pair to the target (4 place of articulation contrasts, 4 voicing contrasts, and 2 manner contrasts). The auditory stimuli were counterbalanced such that each picture in each array was presented once as the target. The frequency of each error type was calculated, as well as proportion correct for each subject's overall performance in each task.

Auditory word comprehension in noise. The auditory comprehension in noise task contains the same word and picture array pairings as the auditory comprehension word-picture matching task described above, except that the auditory stimuli were presented in 14 dB Gaussian white noise. The noise began one second before the onset of the word and ended one second after the end of the word.

Speech Discrimination Measures

The speech discrimination tasks are modeled on previous speech discrimination tasks used with individuals with aphasia (Baker et al. 1981; Blumstein et al. 1977; Caplan & Waters, 1995). Two

discrimination tasks (described below) involved the presentation of pairs of one-syllable words or non-words via headphones while a fixation cross was presented on the computer screen. The same male native English speaker of the words in the comprehension task described above recorded all of the stimuli. There was a one second interval between each syllable in a pair, and five seconds between each pair (more time between pairs was given, if necessary, for the patient's comfort). Patients were instructed to determine if the two syllables presented were the same or different. “Different” trials contained two syllables that differed by one feature of the onset consonant (e.g. “puff” vs “cuff”). The trials comprised of non-word pairs were presented in four arrangements: A-B, B-A, A-A, and B-B such that for half of the trials the correct answer was "same", and for the other half the correct answer was "different". In the "same" trials, two different tokens of the same syllable were presented. Patients made their response either by speaking their answer or by pointing to the correct answer written in large print on a paper adjacent to the computer screen. Signal detection methods were used to determine how well subjects could discriminate between the same and different pairs by calculating the measure d’ for the real word and non-word speech discrimination tasks, respectively (Swets, 1964).

Word & Non-Word Speech Discrimination Tasks. Both speech discrimination tasks each contained 40 trials. The real word speech discrimination task contained pairs of one syllable real words and the non-word discrimination task contained one-syllable non-words, with neighborhood density and phonotactic probability between the real words and non-words matched as much as possible. The Irvine Phonotactic Online Dictionary (Vaden et al. 2009) was used to select the real words and non-words, and to calculate neighborhood density and phonotactic probability for each word and non-word. Each word and its corresponding non-word

have the same onset consonant phoneme. Paired-samples t-tests comparing each word with its matched non-word indicate that there is no significant difference between the two stimulus types for density $t(39) = .14$, $p = .88$ or phonotactic probability $t(39) = .18$, $p = .86$. The words used in the discrimination task do not overlap with the words in the auditory comprehension tasks described above, but the minimal pairs in the speech discrimination tasks are the same minimal pairs present in the auditory word comprehension tasks.

Neuroimaging

All stroke and lobectomy participants (n=162) underwent MRI scanning using a 3T or 1.5T MRI system at the respective testing site. T1-MRIs and T2-MRIs with 1 mm^3 resolution were collected and used to demarcate the lesion; the lesion demarcation was conducted manually by well-trained and experienced individuals in lesion-mapping studies. The lesion maps were smoothed with a 3mm full-width half maximum Gaussian kernel to remove jagged edges associated with manual drawing. Enantiomorphic normalization (Nachev *et al.* 2008) was conducted using SPM12 and ‘in house’ Matlab scripts in the following way: a mirrored image of the T1 image (reflected around the midline) was coregistered to the native T1 image. Then, we created a chimeric image based on the native T1 image with the lesioned tissue replaced by tissue from the mirrored image (using the smoothed lesion map to modulate this blending, feathering the lesion edge). SPM12's unified segmentation-normalization (Ashburner & Friston, 2005) was used to warp this chimeric image to standard space, with the resulting spatial transform applied to the actual T1 image as well as the lesion map. The normalized lesion map was then binarized, using a 50% probability threshold.

Lesion-Symptom Mapping (LSM)

All of the LSM routines used here are integrated into the NiiStat toolbox for Matlab (http://www.nitrc.org/projects/niistat). The following routines were performed: Univariate analyses fitting a general linear model (GLM) were completed to identify localized brain damage associated with auditory comprehension in noise and discrimination. A GLM was fit for performance on each task within each of the 94 left hemisphere regions of interest (ROIs) defined by the John's Hopkins University (JHU) atlas (Mori *et al.* 2008; Faria *et al.* 2012; den Ouden *et al.* 2019). An ROI approach, compared to voxel-based statistics, increases statistical power by reducing the severity of multiple comparison correction (Rorden et al. 2009). Univariate analyses were conducted for the following variables: auditory word comprehension in noise (proportion correct), word discrimination (d') and non-word discrimination (d'). Clear speech auditory word comprehension was not used for LSM due to a ceiling effect with insufficient variability; we discuss this further below. The behavioral data were significantly skewed (i.e. Z-Skew > 1.96) thus de-skewing was performed in NiiStat prior input into the GLM by computing the standard error of the skew and applying a square root transform to the data.

Permutation thresholding included 4,000 permutations to correct for multiple comparisons ($p < 0.05$ controlled for familywise error). As ROIs that are infrequently damaged will have low statistical power while increasing the number of comparisons, only ROIs where at least 11 participants (i.e. approximately 10% of the largest left hemisphere patient sample size in a task)

had damage were included in the analyses. Data collection site was used as a covariate, to remove variance accounted for by collection site. All reported coordinates are in MNI space. Figure 3 displays the extent of coverage of the ROIs included in the lesion-symptom mapping analyses; the coverage does not vary between the analyses.

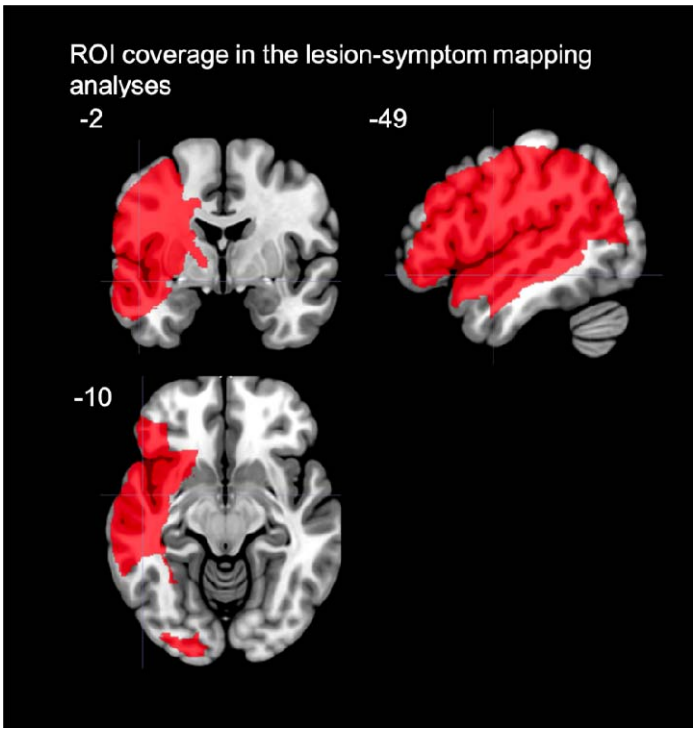

Figure 3. Map of the extent of coverage by the ROIs from the JHU atlas included in the lesion-symptom mapping analyses of the left hemisphere group.

Post-hoc comparisons of LSMs

Based on the results of the LSMs described above, we decided to use conjunction and independence tests to further investigate the relationships between the real word speech

discrimination versus non-word speech discrimination LSM findings, and also between the non-word discrimination vs auditory comprehension in noise LSM findings. The conjunction tests were computed using an in-house Matlab script on the significant ROIs from the LSMs, following the valid conjunction test procedure recommended by Nichols et al. (2005). This conjunction analysis procedure identifies ROIs (at $p < .05$) in which damage is associated with lower performance in both tasks of interest. The independence tests were computed using a custom contrast in the nii_stat toolbox (e.g. 1 -1) to determine if damage in each ROI is significantly more related to one task than the other ($p < .05$, Freedman-Lane permutation as described by Winkler et al. 2014).

Due to a combination of time limitations and site-specific testing protocols, not all participants completed all speech perception tasks. Table 1 indicates the sample sizes for each task within each participant group. Within each lesion group, there are no qualitative differences in the lesion distributions or lesion sizes of the participants who did and did not complete each task.

Results

Overall Behavioral Results

A summary of the descriptive statistics for each group on each of the tasks is presented in Table 1.

	Clear Auditory Word Comprehension				
	Control	**LH Stroke**	**RH Stroke**	**Left ATL**	**Right ATL**
n	21	111	19	18	8
Mean	1	0.97	0.99	1	1
Median	1	1	1	1	1
Std. Deviation	0	0.08	0.03	0	0
Range	1-1	0.4-1	0.9-1	1-1	1-1

	Auditory Word Comprehension in Noise				
	Control	**LH Stroke**	**RH Stroke**	**Left ATL**	**Right ATL**
n	22	94	19	17	8
Mean	0.91	0.770	0.88	0.87	0.91
Median	0.9	0.8	0.9	0.85	0.9
Std. Deviation	0.05	0.15	0.05	0.07	0.05
Range	0.85-1	0.3-1	0.8-0.95	0.75-1	0.85-1

	Word Speech Discrimination				
	Control	**LH Stroke**	**RH Stroke**	**Left ATL**	**Right ATL**
n	25	80	18	17	8
Mean	5.05	4.16	4.72	5.02	5.15
Median	5.15	4.22	5.15	5.15	5.15
Std. Deviation	0.29	1.08	0.78	0.38	0
Range	4.22-5.15	1.71-5.15	2.68-5.15	3.86-5.15	5.15-5.15

	Nonword Speech Discrimination				
	Control	**LH Stroke**	**RH Stroke**	**Left ATL**	**Right ATL**
n	23	79	18	17	8
Mean	4.79	3.69	4.29	4.58	4.76
Median	5.15	4.22	4.22	5.15	5.15
Std. Deviation	0.57	1.30	1.02	0.86	0.56
Range	3.61-5.15	0-5.15	2.07-5.15	2.68-5.15	3.86-5.15

Table 1. Descriptive statistics for the clear auditory word comprehension (proportion correct), auditory word comprehension in noise (proportion correct), word speech discrimination (d-prime values), and non-word speech discrimination (d-prime values) tasks.

Auditory word comprehension task: all groups were at ceiling on the clear speech condition. In the left hemisphere stroke group, the mean performance was 97% correct (Figure 4) with both the left and right anterior temporal lobectomy groups scoring at 100% correct. More variance in performance was found on the speech in noise task, enabling statistical analyses. A one-way ANOVA across the 5 groups (control, LH stroke, RH stroke, L lobectomy, R lobectomy) revealed a significant group effect in performance on the comprehension in noise test ($F(4, 176) = 10.58$, $p < .001$) with the LH Stroke group differing from all other groups (*p*s ≤ .002, Bonferroni correction of $\alpha = .05/10 = .005$) and no other group differences (Figure 5, left panel).

Word and non-word discrimination tasks: A 5 x 2 mixed ANOVA was computed for the performance on the two speech discrimination tasks in each of the five groups revealing significant main effects of Task ($F(1,140) = 18.90$, $p < .001$) with higher scores on the word than nonword discrimination, and Group ($F(4, 140) = 9.20$, $p < .001$). The interaction was not significant ($F(4,140) = 0.37$, $p=.833$). The LH Stroke group performed significantly worse than the control, L lobectomy, and R lobectomy groups (*p*s ≤ .002, Bonferroni correction of $\alpha = .05/10 = .005$) with no other significant group differences. The LH stroke group numerically performed worse than the RH stroke group across both speech discrimination tasks, but the comparison did not withstand multiple comparison correction ($p < .014$) (Figure 5, right panel).

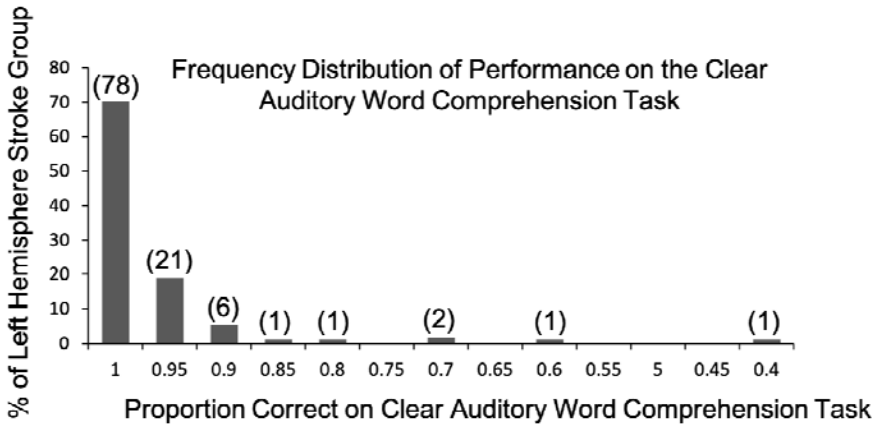

Figure 4. Distribution of performance of the left hemisphere stroke group on the clear auditory comprehension task. Numbers in parentheses indicate the actual number of left hemisphere stroke participants who performed at that accuracy level (out of a total 111 who completed the task). Note that chance performance would be .25 proportion correct (not shown).

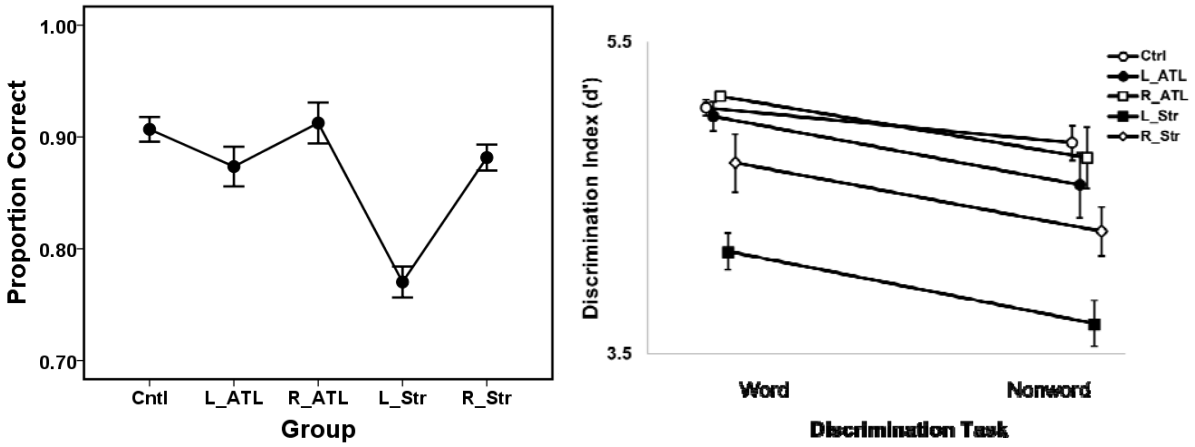

Figure 5. Performance on the auditory word comprehension in noise (left) and speech discrimination tasks (right) in each participant group. Error bars represent standard error.

Overlapping points in the discrimination task graph have been offset slightly to make them visible. ATL = lobectomy, Str = Stroke.

As noted in the introduction, previous observations indicated that performance on auditory word comprehension and syllable discrimination tasks doubly dissociate. We assessed this in our sample by categorizing performance as impaired or spared on the auditory word comprehension in noise task and the word speech discrimination task. Impaired was defined as performance greater than two standard deviations below the control mean; spared was defined as performance that is within or above .5 standard deviations of the control mean. Seventy-nine LH Stroke patients completed both of these tasks. Table 2 presents participant counts that fall into the 4 possible spared-impaired categories on the two tasks. A double dissociation is apparent, with 15 cases (19.0%) exhibiting impaired performance on the auditory word comprehension task but spared performance on the speech discrimination task, and 9 cases (11.3%) showing the reverse pattern. There are fewer cases with spared auditory word comprehension in noise in the face of impaired word discrimination but recall that performance on *clear* word comprehension is at ceiling for the majority of LH Stroke patients. There are 59 such patients who were both at ceiling on the clear auditory word comprehension task and completed the word speech discrimination task; 30 (50.8%) were impaired on the latter, which was also presented as clear speech. This provides substantial evidence for the dissociability of these tasks.

		Word Discrimination	
Noisy Word Comprehension		Impaired	Spared
	Impaired	28	15
	Spared	9	13

Table 2. Frequency counts of LH Stroke cases that fall into the four categories of impaired and spared performance. Impaired is defined as performance that is > 2 standard deviations below the control mean; spared is defined as performance that is within or above .5 standard deviations of the control mean.

Within the LH stroke group, correlation analyses performed between the auditory word comprehension in noise and word speech discrimination tasks revealed a significant relation (N = 79, r = .44, $r^{2 =}$ .19, *p* <.001). However, it is evident from the scatterplot in Figure 6, that variation in performance on one task is a rather poor predictor of variation on the other, accounting for only 19% of the variation.

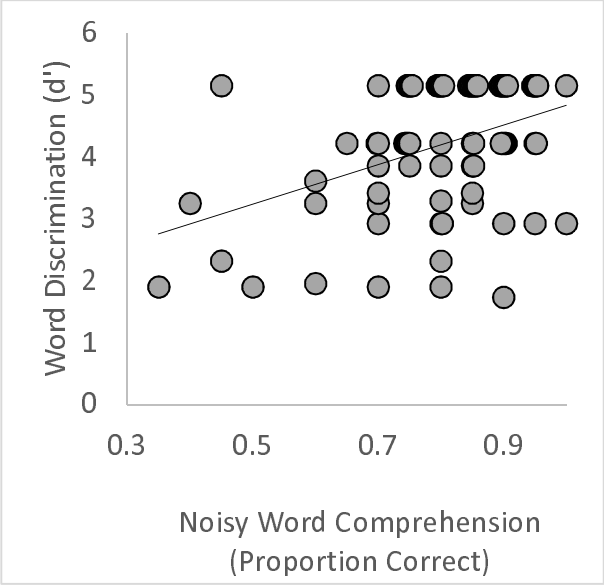

Figure 6: Relation between Auditory Word Comprehension in Noise and Word Speech Discrimination tasks within the LH stroke group. Overlapping points have been offset slightly to make them visible.

Lesion-behavior mapping results

Lesion-symptom mappings (LSM) were computed within the left hemisphere patients for auditory word comprehension in noise, word discrimination and non-word discrimination. The auditory word comprehension in noise task identified five adjacent ROIs covering much of the superior temporal lobe (Table 3). These ROIs included the superior and middle temporal gyri and underlying white matter, as well as extending into the inferior portion of the supramarginal gyrus; Heschl's gyrus also was implicated as it is part of the anterior superior temporal ROI identified (anterior portion of ROI cluster: peak *z* of the ROI cluster = 3.08, center of mass = MNI coordinates -51 -12 2; posterior portion of ROI cluster: peak *z* of the ROI cluster = 3.67, center of mass = MNI coordinates -56 -47 5) (Figure 7A). The LSM of word speech discrimination identified two significant ROIs ($p < .05$, corrected; Table 3) adjacent to one another (Figure 7B), implicating most of the STG, as well as Heschl's gyrus and the planum temporale (peak $z = 3.67$, center of mass = -49 -24 3 MNI), as well as an additional significant ROI, consisting of a portion of the superior longitudinal fasciculus (SLF) underlying the supramarginal gyrus (peak $z = 3.46$; center of mass = -35 -24 29 MNI). The LSM of non-word speech discrimination identified the ROIs implicated in real word speech discrimination (peak $z = 3.50$ in the superior temporal ROIs, and 3.30 in the SLF), as well as an additional ROI in the supramarginal gyrus extending into the post-central gyrus (peak $z = 2.87$, center of mass = -51 -29 33 MNI), which is dorsal to the supramarginal gyrus region implicated in the auditory word comprehension in noise LSM (Figure 7B). All three LSMs overlap in the ROI that includes

posterior portions of the superior temporal gyrus as well as more mid-temporal regions including Heschl's gyrus (orange, Figure 7C; Table 3).

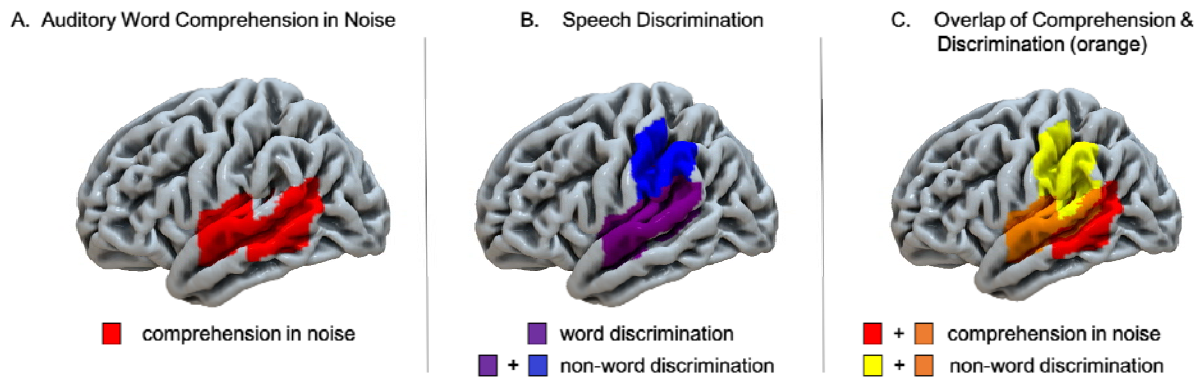

Figure 7. Brain regions implicated in each task in the left hemisphere stroke group, $p < .05$, permutation-based family-wise error corrected. (A) Left lateral view of the regions significantly implicated in auditory word comprehension in noise (B) Left lateral view of the regions significantly implicated in word and non-word speech discrimination. Note that the word speech discrimination regions are a subset of the regions implicated in non-word speech discrimination. (C) Overlap of auditory word comprehension in noise and non-word speech discrimination indicated in orange.

JHU atlas ROI description (ROI number and label)	Auditory Word Comprehension in Noise	Speech Discrimination: Real Words	Speech Discrimination: Non-words
Left supramarginal gyrus (29 SMG_L)	--	--	2.87
Left superior temporal gyrus (35 STG_L)	3.04	3.27	3.49
Left rentrolenticular part of internal capsule (135 RLIC_L)	3.08	--	--
Left Sagittal stratum* (151 SS_L)	3.67	--	--
Left superior longitudinal fasciculus (155 SLF_L)	--	3.46	3.30
Left posterior superior temporal gyrus (184 PSTG_L)	--	3.67	3.60
Left posterior middle temporal gyrus (186 PSMG_L)	3.29	--	--

Table 3. Peak z-scores in each significant ROI in the auditory word comprehension in noise and speech discrimination tasks.

**the JHU ROI atlas notes that the sagittal stratum inc0ludes inferior longitudinal fasciculus and inferior fronto-occipital fasciculus.*

The results for the post-hoc conjunction and independence tests of the LSMs are as follows: for the real word speech discrimination versus the non-word speech discrimination (LSMs shown in Figure 7B), the conjunction test identified the left superior temporal gyrus, the left posterior superior temporal gyrus, and the left superior longitudinal fasciculus ROIs (i.e. all three ROIs

that were separately significant for each task (Table 3)); the independence test did not identify any ROIs as being significantly more implicated in the non-word than the real word speech discrimination. For the non-word speech discrimination versus auditory comprehension in noise LSMs (LSMs shown in Figure 7C), the conjunction test identified damage in the left superior temporal gyrus ROI as being significantly related to lower performance in both tasks; the independence test identified damage in the left supramarginal gyrus, left posterior superior temporal gyrus, and left superior longitudinal fasciculus ROIs as being significantly more related to lower performance for non-word speech discrimination than for auditory comprehension in noise, and damage in the posterior middle temporal gyrus and sagittal striatum ROIs as being significantly more related to lower performance for auditory comprehension in noise than for non-word speech discrimination. In short, the findings from the post hoc conjunction and independence analysis statistically confirm the map shown in Figure 7C.

Right Hemisphere Results

To test for effects of right hemisphere damage on speech perception, we partitioned the RH Stroke group into those cases with ("Temporal +") or without ("Temporal – ") damage (Figure 2 A,B) to posterior superior temporal gyrus and compared them to controls on the auditory word comprehension in noise task and the speech discrimination tasks. The one-way ANOVA across the three groups (RH Temporal +, RH Temporal -, and control) on the auditory word comprehension in noise task yielded a borderline significant effect of group ($F(2, 40) = 3.03$, $p = .061$), with the superior temporal lobe damaged group performing numerically worse than those without damage there (Figure 8, left panel). A mixed ANOVA on the two speech discrimination

tasks across the same three groups revealed a significant effect of Task (F(1, 38) = 7.4, p = .01) with nonword discrimination performance lower than word discrimination, and a significant effect of Group (F(2, 38) = 7.5, p = .002), with the RH Temporal + group performing significantly worse than the controls and the RH Temporal- group (*p*s<.002, Bonferroni correction of α = .05/3 =.017); there was no significant difference between the control group and the RH Temporal- group (Figure 8, right panel). The Task x Group interaction was not significant (F(2,38) = 1.5, p=.24).

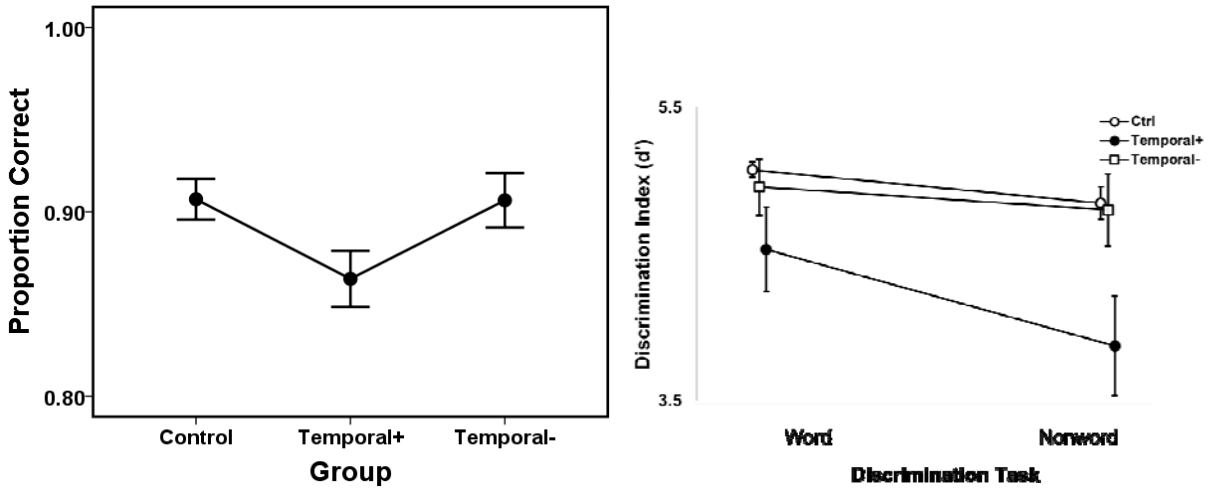

Figure 8. Right hemisphere auditory word comprehension in noise (left panel) and speech discrimination performance (right panel). Error bars represent standard error. Overlapping points in the speech discrimination graph have been offset slightly to make them visible.

Discussion

The present study examined auditory word comprehension and speech discrimination tasks in stroke patients, anterior temporal lobectomy patients, and unimpaired controls to examine four prominent functional-anatomical models of speech processing regarding the critical neural substrates of single word comprehension and discrimination. Consistent with prior work, we found that performance on auditory comprehension and speech discrimination tasks dissociate behaviorally[2]. We also found distinguishable lesion patterns on the two types of tasks, clearly showing that non-identical networks are involved in successful task performance (Hickok & Poeppel, 2000, 2004, 2007). Overall our results provide strong support for the view that receptive speech processing is bilaterally supported and involves the mid-to-posterior superior temporal gyrus as well as the posterior middle temporal gyrus; performance on speech discrimination tasks additionally recruits dorsal stream areas in the planum temporal and inferior parietal lobe. A simple interpretation of bilateral models of speech perception (Gazzaniga & Sperry, 1967; Zaidel, 1985; Buchman et al. 1986; Bachman & Albert, 1988; Goodglass, 1993; Hickok & Poeppel 2000, 2004, 2007) predicts some degree of speech perception deficit following left *or* right hemisphere damage. We report significantly lower performance for patients with right temporal lobe damage than controls or right hemisphere patients with the temporal lobe spared on the speech discrimination tasks, and a similar trend approaching significance for the auditory word comprehension in noise task. To our knowledge, this is the first direct evidence for a speech perception impairment following unilateral right hemisphere damage. Consistent with this finding, a recent TMS study reported similar effects when left or

[2] One possible explanation of this dissociation might be general task difficulty differences, but there are two strong pieces of evidence against a general task difficulty effect and indicating a speech perception-related effect: (1) the ROIs identified are in auditory-related areas and not frontal regions typically implicated in task demands, and (2) the vast majority of the errors induced by adding noise were phonemic errors (i.e. selecting the phonemic foil picture).

right superior temporal regions were interrupted in healthy participants (Kennedy-Higgins et al. 2020).

To examine the neural correlates of speech processing within the left hemisphere, ROI-based lesion-behavior maps were generated for the auditory word comprehension in noise task and the two speech discrimination tasks in the LH Stroke sample (Figure 7). The major findings include the following. Impaired performance on the auditory word comprehension in noise task mapped onto a set of regions in the superior temporal and middle temporal gyri, consistent with a previous study of auditory word comprehension using lesion-connectome mapping (Bonilha *et al*. 2017). It is noteworthy that the auditory word comprehension in noise LSMs did not implicate structures in the dorsal stream including frontal motor-related areas thought to be implicated for perception of speech in noise (Wilson, 2009) nor the posterior planum temporal region likely to include auditory-motor area Spt (Hickok, 2012; Hickok *et al.* 2011; Rogalsky *et al*. 2015) nor dorsal white matter pathways. This finding provides strong support for the view that word comprehension, even under noisy listening conditions, is supported by ventral stream temporal lobe systems. Both of the speech discrimination tasks also implicated the mid-to-posterior superior temporal gyrus, providing strong support for the view that this is a critical region for phonemic perception, but did not implicate the MTG, which has been linked to higher-level word (lemma) processing (Binder et al. 2000; Hickok & Poeppel, 2007; Lau et al. 2008). The lesion maps for the speech discrimination tasks also extended dorsally into the parietal operculum as well as into the planum temporal region including auditory-motor area Spt (Hickok et al. 2003, 2011; Hickok, 2012; Rogalsky et al. 2015). The speech discrimination tasks also implicated white matter in the superior longitudinal fasciculus underlying the supramarginal

gyrus and the non-word task additionally implicated adjacent portions of the supramarginal gyrus. This lesion pattern of involvement for the different tasks was confirmed by the post-hoc conjunction and independence tests.

The lesion-behavior maps provide support for the role of the left mid and posterior superior temporal and inferior parietal regions in phonemic perception and auditory word comprehension (in noise). However, this does not preclude a bilateral representation of speech processing: it is noteworthy that all groups were at ceiling on the clear auditory word comprehension task. Even in the left hemisphere stroke group, the mean performance was 97% correct. The left anterior temporal lobectomy group performed even better, scoring 100% correct. This confirms past reports that chronic left hemisphere damage, including anterior temporal regions, does not substantially impair speech recognition even in a context that requires listeners to make subtle phonemic (e.g., bear vs. pear) or semantic (e.g., bear vs. moose) distinctions on common words (Bachman & Albert, 1988), except in rare cases as discussed below. One may wonder whether plastic reorganization is responsible for this effect with the right hemisphere taking on the speech recognition function after left hemisphere insult. However, acute stroke (Rogalsky et al. 2008) and acute left hemisphere deactivation (Hickok et al., 2008) studies report similar results.

Consistent with Wernicke's 1874 proposal, the ability to perceive speech (as measured by our auditory word comprehension in noise and speech discrimination tasks) implicates the mid-to-posterior superior temporal gyrus, classical Wernicke's area. This was demonstrated directly in our left-hemisphere damaged sample using lesion-behavior mapping and was evident on all three tasks. Three additional observations from the present study indicate that the system is bilaterally

organized. First, deficits following unilateral left hemisphere lesions were well above chance level, even on the nonword speech discrimination task. Indeed, only six of the LH stroke cases performed below discrimination threshold on the nonword speech discrimination task and the lowest score on the word speech discrimination task was above threshold (d' = 1.71). (Threshold is conventionally set at d' = 1, which roughly corresponds to 75% correct.) Second, performance on the clear auditory word comprehension task, which also required differentiating between similar phonemes, was at or near ceiling (≥ 90%) for 92.3% of the LH stroke cases. This shows that unilateral damage does not substantially impair phonological analysis during clear auditory word comprehension except in relatively rare cases, between 5 and 10% in the present study. Interestingly, the incidence of anomalous cerebral lateralization for language in strong right handers is in that same ballpark with estimates at approximately 5% (Knecht, *et al.* 2000). This is broadly consistent with the view that rare cases of clear speech unilateral impairment may reflect some form of statistically atypical organization. Indeed, functional brain imaging work suggests the incidence of almost complete left dominance is itself atypical and with a frequency of approximately 5% (Springer, *et al.* 1999). Third, we directly documented, for the first time, impairment in phonemic discrimination following *right* superior temporal lobe damage. Previous evidence provides further support for the bilateral model: (i) bilateral superior temporal lesions are associated with profound speech comprehension and identification deficits (word deafness) (Buchman *et al*. 1986; Poeppel, 2001); (ii) acute left hemisphere deactivation (Wada procedure) does not profoundly impair auditory word comprehension (Hickok *et al.* 2008); and (iii) the right hemisphere of split brain patients has good auditory comprehension at the word level (Zaidel, 1985; Gazzaniga & Sperry, 1967). The data point strongly to bilateral capacity of speech perception, including phonemic discrimination and auditory word comprehension. This does not,

however, necessarily imply symmetry of function (Zatorre *et al.* 2002; Poeppel, 2003; Hickok & Poeppel, 2007; Morillon *et al.* 2010). Indeed, we found greater impairment following left compared to right hemisphere damage on our auditory word comprehension in noise task as well as our discrimination tasks. This could reflect left-right computational differences within the STG/STS speech perception system (Poeppel, 2001; Zatorre *et al.* 2002) or their interaction with other more lateralized networks—lexical, sensorimotor—that augment the efficiency of the left hemisphere for processing speech for some tasks.

The lesions associated with deficits on both of the speech discrimination tasks extended dorsally into the parietal operculum, which includes auditory cortical fields (Galaburda & Sanides, 1980) as well as secondary somatosensory cortex (Ruben, *et al.* 2001). For the nonword speech discrimination task the lesion distribution extended more dorsally still into the parietal-temporal area and the supramarginal gyrus. This finding is consistent with Hickok and Poeppel's (2000) hypothesis that the superior temporal gyrus is the primary substrate for the analysis of speech sounds, but then "there is a divergence in the processing stream, with one stream involving more ventral– posterior structures, which play a role in auditory comprehension, and the other stream involving more dorsal–anterior systems, which play a greater role in sub-lexical speech tasks" (p. 135). They argued that this task-dependent divergence is rooted in the involvement of phonological working memory on "sub-lexical" (here, nonword) tasks, which cannot take advantage of semantic codes for task performance. Phonological working memory networks, in turn, were argued to be dependent on dorsal sensorimotor networks critical for speech production, which is by now fairly well-established (Hickok *et al.* 2003; Buchsbaum & D'Esposito, 2019; Buchsbaum *et al.* 2011; Schomers *et al.* 2017; McGettigan *et al.* 2011).

Thus, the task effects reported in the present study can be interpreted straightforwardly. All tasks implicate the STG because this is the primary substrate for speech perception and damage there partially disrupts acoustic-phonetic-phonological analysis of the signal, which is necessary for all receptive speech tasks. The nonword speech discrimination task additionally implicates dorsal stream structures in the posterior planum temporal region (e.g. Hickok et al. 2003, 2011), the inferior parietal lobe, and underlying dorsal stream white matter tracts because this task places additional demands on phonological working memory, which is supported by sensorimotor networks for speech production. The auditory word comprehension in noise task directly involves the ventral stream network including STG speech analysis systems and MTG lexical-semantic networks (Liebenthal et al. 2005; Hickok & Poeppel, 2007; Lau et al. 2008; Pillay et al. 2017) but not dorsal stream regions. The word speech discrimination task falls in between as it has both the possibility of using the phonological working memory route and a lexical-semantic route placing less demand on the dorsal stream.

The present study also clarifies the role of the anterior temporal lobe in speech perception and comprehension. For all tasks, the stroke-based analyses implicated mid-posterior as well as mid-anterior STG regions. The mid-anterior STG ROI extended anteriorly such that it nearly included the coordinates for fMRI activations in the ATL that have been claimed to be the foci involved in intelligible speech processing (Figure 9), as revealed in studies of intelligible versus unintelligible sentences (Scott *et al.* 2000; Narain *et al.* 2003; Evans *et al*. 2014).

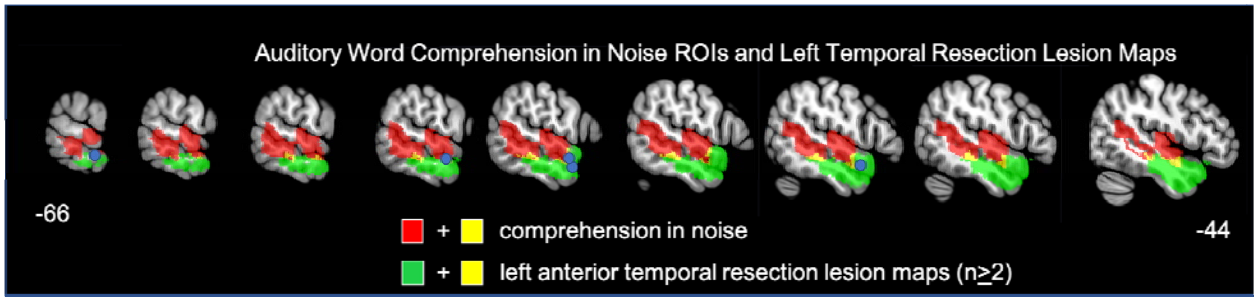

Figure 9. Red: Significant ROIs identified by the LSM analyses for the auditory word comprehension in noise task; Green: The left lobectomy group's lesion maps (areas shown indicate lesion in at least 2 subjects); Yellow: overlap between the auditory comprehension in noise ROIs and the left lobectomy lesion maps. Blue circles indicate the five anterior temporal coordinates identified by Scott et al. 2000 (MNI: -54 6 -16, -66 -12 -12) or Evans et al. 2014 (MNI: -58 2 -16, -60 -2 -12, -58 4 -20) as exhibiting main effects of speech intelligibility or a similar contrast.

These activation foci largely fall within the region impacted by ATL resection cases, which as a group scored lower than controls and similar to the group average for right posterior temporal strokes, but quite a bit better than the left hemisphere stroke group. This suggests a role for the left ATL in speech processing, but more broadly, our findings unequivocally disconfirm the claim that the *left* ATL forms the primary pathway for intelligible speech processing (Scott et al. 2000). The critical network defined by our speech discrimination and auditory word comprehension in noise tasks instead identify both anterior and posterior superior temporal regions, and does so bilaterally as more recent functional imaging work on intelligible speech has shown (Evans et al. 2014; Okada et al. 2010).

In summary, the findings from the present study support a neuroanatomical model of basic auditory word identification and comprehension in which the critical region involves much of the superior temporal lobe, bilaterally: a hybrid of models (2) and (3) in the introduction. This work also confirmed the dissociability, both behaviorally and anatomically, of comprehension- and discrimination-based auditory speech tasks. Given that a large of number of studies of "speech perception" use discrimination-type tasks, particularly those that implicate dorsal, motor-related networks (D'Ausilio et al. 2009; Meister et al. 2007; Mottonen et al. 2009), the present finding calls for a critical re-evaluation of that body of work.

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Competing Interests

None

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