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The Role of Planum Temporale in Processing Accent Variation in Spoken Language Comprehension

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Abstract: A repetition–suppression functional magnetic resonance imaging paradigm was used to explore the neuroanatomical substrates of processing two types of acoustic variation—speaker and accent—during spoken sentence comprehension. Recordings were made for two speakers and two accents: Standard Dutch and a novel accent of Dutch. Each speaker produced sentences in both accents. Participants listened to two sentences presented in quick succession while their haemodynamic responses were recorded in an MR scanner. The first sentence was spoken in Standard Dutch; the second was spoken by the same or a different speaker and produced in Standard Dutch or in the artificial accent. This design made it possible to identify neural responses to a switch in speaker and accent independently. A switch in accent was associated with activations in predominantly left-lateralized areas including posterior temporal regions, including superior temporal gyrus, planum temporale (PT), and supramarginal gyrus, as well as in frontal regions, including left pars opercularis of the inferior frontal gyrus (IFG). A switch in speaker recruited a predominantly right-lateralized network, including middle frontal gyrus and prenuneus. It is concluded that posterior temporal areas, including PT, and frontal areas, including IFG, are involved in processing accent variation in spoken sentence comprehension. *Hum Brain Mapp 00:000–000, 2011.* © 2011 Wiley-Liss, Inc.

Key words: repetition–suppression; speech; speaker; auditory cortex

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INTRODUCTION

The human speech comprehension system seems to effortlessly extract the linguistic message from the acoustic signal. This is a remarkable feat, given the variability inherent to this signal, for instance, as a result from speaker differences [Peterson and Barney, 1952]. These differences are not only anatomical/physiological in nature, but also emerge from social factors such as a speaker's geographical background and socioeconomic status. These social factors result in different spoken varieties of the standard

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language, which can be exemplified by phonetic and phonological variation in the sounds of a language [Wells, 1982]. For instance, the Dutch word *bed* (bed) is pronounced with the vowel/ɛ/in the western part of the Netherlands, but with a vowel close to/a/as in *bad* (bath) in the south-eastern part [Adank et al., 2007]. Listeners are continuously confronted with ambiguities in speech that they have to resolve perceptually (or, *normalize*) to extract the linguistic message [Nearey, 1989]. This disambiguating process requires cognitive effort; reflected in longer response times for comprehension of sentences spoken with an unfamiliar regional or foreign accent compared to listeners' native accent [Adank et al., 2009; Floccia et al., 2006; Rogers et al., 2004; Van Wijngaarden, 2001].

Behaviorally, listeners process accented speech by shifting their phonetic boundaries to match those of the speaker, when confronted with a speaker whose speech displays accent or specific idiosyncrasies [Evans and Iverson, 2003; Norris et al., 2003]. It has finally been suggested that the adaptation process involves pattern matching mechanisms [Hillenbrand and Houde, 2003; Nearey, 1997] that are based on statistical learning [Nearey and Assmann, 2007].

The neural bases underlying processing of accent-related variation are largely unknown. It has been hypothesized that the planum temporale (PT) is involved in processing complex spectrotemporal variation in speech [Griffiths and Warren, 2002; Warren et al., 2005]. PT is a large region in the temporal lobe, posterior to Heschl's gyrus in the superior temporal gyrus (STG), and represents the auditory association cortex. PT is involved in elementary acoustic pattern perception [Binder et al., 2000; Giraud et al., 2000; Hall et al., 2002; Penhune et al., 1998], spatial processing [Warren et al., 2005] auditory scene analysis [Bregman, 1990], musical perception [Zatorre et al., 1994], and, more specifically, speech perception, [Binder et al., 1996; Giraud and Price, 2001; Shtyrov et al., 2000]. PT is hypothesized to be involved in continuous updating of incoming traces required for phonological working memory and speech production [Binder et al., 2000]. Griffiths and Warren [2002] propose a functional model for the processing in PT of spectrotemporally complex sounds that change over time. PT continuously analyses these incoming signals and compares them with those previously experienced using pattern matching. Griffiths and Warren furthermore suggest that PT is associated with "...constructing a transient representation of the spectrotemporal structures embodied in spoken words, regardless of whether these are heard or retrieved from lexical memory (i.e., a phonological template.)".

The present study aimed to provide insights into the neural locus of processing accent and speaker variation using functional magnetic resonance imaging (fMRI). We investigated whether PT is involved in disambiguation processes required for understanding accented speech using a repetition–suppression fMRI design. Repetition suppression is based on the finding that the repeated presentation of a stimulus induces a decrease in brain activity. This decrease can be detected using fMRI [Grill-Spector and Malach, 2001; Grill-Spector et al., 1999]. This technique can be used to identify brain areas involved in processing specific stimulus characteristics. By varying the property that is repeated, the neural bases involved in processing that specific property are uncovered. For example, repetition–suppression paradigms have been used to locate the neural substrates of speaker processing [Belin and Zatorre, 2003], spoken syllables [Zevin and McCandliss, 2005], spoken words [Orfanidou et al., 2006], and spoken sentences [Dehaene-Lambertz et al., 2006].

In the experiment, listeners heard two sentences presented in quick succession. The first sentence was spoken in Standard Dutch; the second sentence was spoken by the same or a different speaker in Standard Dutch or in a novel accent of Dutch. This design allowed us to identify neural responses to a switch in speaker, in accent, or both. Recordings were made for a male and a female speaker of Dutch to maximize the amount of variation related to anatomical/physiological differences between speakers. *Accent* and *speaker* were implemented in a factorial design with both factors crossed, allowing us to determine the neural bases associated with processing both variation types independently. Phonological/phonetic variation was introduced into the speech signal by creating an artificial, nonexisting, accent. Using a nonexisting accent has two advantages: first, speaker and accent were not confounded as both factors were manipulated independently. Second, the use of a novel accent ensures that all listeners are equally unfamiliar with the accent. This is necessary as familiarity with an accent affects language comprehension: processing slow when listeners are unfamiliar with the accent [Floccia et al., 2006], especially in noisy conditions [Adank et al., 2009].

MATERIALS AND METHODS

Participants

Twenty participants (14F and 6M, mean 21.2 years; range, 18–26 years) took part in the study, although the data from two (2F) were subsequently excluded due to (i) to excessive head movement (>3 mm) and (ii) an unexpected brain anomaly. The remaining 18 participants were right-handed, native monolingual speakers of Dutch, with no history of oral or written language impairment, or neurological or psychiatric disease. All gave written informed consent and were paid for their participation. The study was approved by the local ethics committee.

Experiment and Design

The present repetition–suppression fMRI experiment used a miniblock design, with continuous scanning. The choice of continuous rather than sparse sampling was

TABLE I. Experimental conditions: speaker and accent of the second sentence in the design

Name	Speaker	Accent
SS	Same speaker	Same accent
DS	Different speaker	Same accent
DA	Same speaker	Different accent
DSDA	Different speaker	Different accent

The first sentence was always spoken in Standard Dutch.

based on a trade-off between the ability to reliably detect suppression in the blood oxygen level-dependent (BOLD) signal and the length of the experiment. Continuous sampling results in both acoustic masking of the auditory sentences [Shah et al., 1999] and contamination of the BOLD signal response in auditory regions [Bandettini et al., 1998; Hall et al., 1999; Talavage et al., 1999]. The former, however, was not a problem as a relatively quiet acquisition sequence (~80 dB) coupled with sound attenuating headphones (~30 dB attenuation) ensured that the sentences were easily heard. Indeed, all participants confirmed their ability to hear and understand the sentences during a familiarization session in which only sentences in Standard Dutch (not included in the main experiment) were presented. Contamination of the BOLD signal was potentially more problematic, because scanner noise elevates BOLD responses in auditory areas [Gaab et al., 2006; Hall et al., 1999], and these effects need not be identical across regions [Tamer et al., 2009; Zaehle et al., 2007]. In the current experiment, however, we were specifically interested in relative *reductions* in BOLD signal. As a result, elevated BOLD responses may not be problematic; only responses driven to saturation levels by the scanner noise would reduce sensitivity, and previous studies have clearly shown that typical EPI sequences reduce, but do not eliminate, the dynamic range of the BOLD response [Gaab et al., 2006; Zaehle et al., 2007]. Moreover, to avoid scanner-noise contamination and ensure an adequate sampling of the evoked hemodynamic response function requires silent periods between volume acquisitions lasting between 16 and 32 s [Eden et al., 1999; Edmister et al., 1999; Hall et al., 1999; Hickok et al., 1997; Tamer et al., 2009]. A sparse design would therefore result in the experiment lasting up to twice as long as using a continuous design, which was deemed likely to reduce participants' ability to attend to the sentences. Consequently, we chose to use a continuous sampling paradigm.

Listeners were presented with two sentences in quick succession in four conditions as in Table I. The first sentence was always spoken in Standard Dutch, followed by the same sentence spoken by the same speaker in the same accent (condition SS, same speaker, and same accent), spoken by a different speaker in the same accent (DS, different speaker, same accent, representing a switch of speaker), by the same speaker in a different accent (DS, same speaker, different accent, representing a switch of accent), or finally by a different speaker in a different accent (DSDA, different speaker, different accent, representing a switch of speaker and accent). Thirty-two sentences were presented per condition in eight miniblocks of four stimuli. Participants were required to listen to the sentences and to pay close attention. There was no additional task.

Stimulus Materials

The total stimulus set consisted of 256 sentences. The sentences were taken from the speech reception threshold corpus or SRT [Plomp and Mimpen, 1979]. This corpus has been widely used for assessing intelligibility of different types of stimuli, for example, for speech in noise [Zekveld et al., 2006] or foreign-accented speech [van Wijngaarden et al., 2002]. The SRT consists of 130 sentences designed to resemble short samples of conversational speech. All consist of maximally eight or nine syllables and do not include words longer than three syllables. Two versions of 128 of the SRT-sentences were recorded in Standard Dutch and in the novel accent. The novel accent was designed to merely sound different from Standard Dutch and was not intended to replicate an existing accent.

The novel accent, also used in [Adank and Janse, 2010], was created by instructing the speaker to read sentences with an adapted orthography. The orthography was systematically altered to achieve the following changes in all 15 Dutch vowels: the switching of all tense-lax vowel pairs (e.g.,/e:/was pronounced as/ɛ/and vice versa),/u/(not

TABLE II. Intended vowel conversions for obtaining the novel accent

Orthography	Phonetic (IPA)
a → aa	/a/ → /a:/
aa → a	/a:/ → /a/
e → ee	/ɛ/ → /e:/
ee → e	/e:/ → /ɛ/
i → ie	/I/ → /i:/
ie → i	/i:/ → /I/
o → oo	/ɔ/ → /o:/
oo →o	/o:/ → /ɔ/
uu → u	/y:/ → /Y/
u → uu	/Y/ → /y:/
oe → u	/u/ → /Y/
eu →u	/ø/ → /Y/
au → oe	/ou/ → /u/
ei →ee	/ɛi/ → /e:/
ui → uu	/œy/ → /y:/

The left column shows the altered orthography in Standard Dutch, and the right column shows the intended change in pronunciation of the vowel in broad phonetic transcription, using the International Phonetic Alphabet (IPA, 1999).

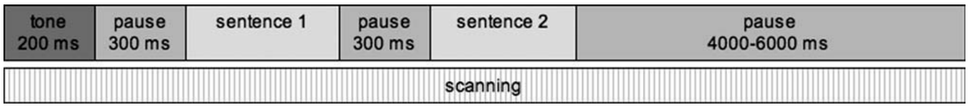

Figure 1.
Timeline of the presentation of a single sentence pair.

having a lax counterpart in Dutch) was pronounced as /Y/, and all diphthongal vowels were realized as monophthongal vowels (e.g.,/εi/was pronounced as/e:/). All changes are listed in Table II, and all sentences are listed in Appendix I. Only vowels bearing primary or secondary stress were included in the conversion of the orthography. An example of a sentence in Standard Dutch and a converted version is given below, including a broad phonetic transcription using the International Phonetic Alphabet [IPA, 1999]:

Standard Dutch: "De bal vloog over de schutting"
/də bɑl flox oːfər də sxʏtɪŋ/
[The ball flew over the fence]
After conversion: "De baal flog offer de schuuttieng"
/də baːl floːx ɔfər də sxyːtiŋ/

These sentences were recorded in both accents by a female and a male speaker of Dutch. The recordings were made in a sound-attenuated booth. Sentences were presented on the screen of a desktop computer. The speakers were instructed to read the sentences aloud as a declarative statement and with primary sentence stress on the first noun, as to keep the intonation pattern relatively constant across all sentences. First, two tokens were recorded of each Standard Dutch version followed by one token of the artificial accent version. Every sentence in the artificial accent was repeated until it was pronounced as instructed and sounded as fluent as the Standard Dutch sentences. The speakers were monitored from sentence to sentence during recording by the first author (a trained phonetician). After recording, the sentences were checked by the first author, and all sentences with mistakes were re-recorded, using the same procedure. Finally, 14 additional sentences were recorded in Standard Dutch for the control task in the fMRI experiment. All sentences were recorded to hard disk directly via an Imix DSP chip plugged into the USB port of an Apple Macbook.

Next, all sentences were saved into separate sound files with begin and end trimmed at zero crossings and resampled at 16 kHz. Subsequently, the speech rate differences across all six tokens of a specific sentence (two Standard Dutch tokens and one artificial accent token, for two speakers) were equalized, so that every token for a given sentence had the same length. This ensured that both sentences in each repetition–suppression stimulus pair were equally long. First, for each of the 128 sentences (four experimental conditions × 32 sentences), the average duration across all six tokens for that sentence was calculated. Second, each token was digitally shortened or lengthened to fit the average length for the sentence, using PSOLA [Moulines and Charpentier, 1990], as implemented in the Praat software package, version 4.501 [Boersma and Weenink, 2003]. Second, every sentence was peak-normalized at 99% of its maximum amplitude and then saved at 70 dB (SPL).

Procedure

The participants listened to the stimuli and were instructed to pay close attention and told that they would be tested after the experiment. A single trial (see Fig. 1) began with a tone signal of 200 ms, followed by a pause of 300 ms, the presentation of the first sentence of the pair (always in Standard Dutch), a pause of 300 ms, and the second sentence of the pair. The interstimulus-interval was effectively jittered by adding a waiting period that was randomly varied between 4,000 and 6,000 ms to the offset of the second sentence. The average sentence duration was 2,495 ms (range, 2,074–3,064 ms).

To improve statistical power, trials occurred in short blocks of four sentences of one experimental condition, followed by a silent baseline trial (duration randomly varied from 4,000 to 6,000 ms). The identity of the speaker did not vary across the first sentences of a pair in a miniblock. Every unique sentence was presented only once in the experiment, and all were presented in a semirandomized order and counterbalanced across conditions, so that the 128 sentences were presented in all four conditions across participants. The presentation of the 128 sentence trials and the 32 silent trials lasted 23 min. Before the main experiment, listeners were presented with six sentences (not included in the main experiment) spoken by the same speaker as in the main experiment to ensure that the sentences were audible over the scanner noise and presented at a comfortable loudness level (adapted for each individual participant).

Participants were informed that the sentences were presented in pairs and that the first sentence of a pair was always spoken in Standard Dutch and that the second one often varied in speaker, accent, or both. They were also informed that the sentence itself did not vary, that is, that they would be presented with two tokens of the same sentence within a stimulus pair. Presenting participants with a sentence in Standard Dutch ensured that they would be able to understand the linguistic message and second that they would not have to make additional cognitive efforts to understand the linguistic content of the second sentence in a pair.

After the main experiment, participants heard 28 single sentences in Standard Dutch. Half of these sentences had not been presented before (these sentences were not part of the SRT corpus, but had been constructed to resemble the SRT sentences as much as possible)—and the other half had been presented in the main experiment. After the main experiment had finished, participants responded through a button-press with their right index finger when they had heard the sentence in the main experiment. Stimulus presentation was performed using Presentation (Neurobehavioral Systems, Albany, CA), running on a Pentium 4 with 2 GB RAM, and a 2.8 GHz processor.

Functional MRI Data Acquisition

Whole-brain imaging was performed at the Donders Centre for Brain, Cognition, and Behaviour, Centre for Cognitive Neuroimaging, at a 3T MR scanner (Magnetom Trio, Siemens Medical Systems, Erlangen, Germany). The sentences were presented over electrostatic headphones (MRConFon, Magdeburg, Germany) during continuous scanner acquisition (GE-EPI, repetition time = 2,282 ms; echo time = 35 ms; 32 axial slices; slice thickness = 3 mm; voxel size = 3.5 × 3.5 × 3.5 mm; field of view = 224 mm; flip angle = 70°)—in other words, over the noise of the scanner. All participants confirmed their ability to hear and understand the sentences during a short practice session when the scanner was on. All functional images were acquired in a single run. Listeners watched a fixation cross that was presented on a screen and viewed through a mirror attached to the head coil.

After the acquisition of functional images, a high-resolution structural scan was acquired (T1-weighted MP-RAGE, 192 slices, repetition time = 2,282 ms; echo time = 3.93 ms; field of view = 256 mm, slice thickness = 1 mm). Total scanning time was 40 min.

Analyses

The neuroimaging data were preprocessed and analyzed using SPM5 (Wellcome Imaging Department, University College London, London, UK). The first two volumes of every functional run from each participant were excluded from the analysis to minimize T1-saturation effects. Next, the image time series were spatially realigned using a least-squares approach that estimates six rigid-body transformation parameters [Friston et al., 1995] by minimizing head movements between each image and the reference image, that is, the first image in the time series. Next, the time series for each voxel was temporally realigned to acquisition of the middle slice. Subsequently, images were normalized onto a custom Montreal Neurological Institute (MNI)-aligned EPI template (based on 28 male brains acquired on the Siemens Trio at the Donders Institute for Brain, Cognition and Behaviour, Centre for Neuroimaging) using both linear and nonlinear transformations and resampled at an isotropic voxel size of 2 mm. All participants' functional images were smoothed using an 8-mm FWHM Gaussian filter. Each participant's structural image was spatially co-registered to the mean of the functional images [Ashburner and Friston, 1997] and spatially normalized with the same transformational matrix applied to the functional images. A high-pass filter was applied with a 0.0078 Hz (128 s) cut-off to remove low-frequency components from the data, such as scanner drifts.

The fMRI time series were analyzed within the context of the General Linear Model using an event-related approach. Repetition suppression was operationally defined as the difference between stimulus pairs for each of the four condition (SS, DS, DA, and DSDA), following Noppeney and Penny's [2006] *categorical* approach for analyzing repetition–suppression designs (see also [Chee, 2009; Chee and Tan, 2007; Henson et al., 2004]). The rationale behind this approach is as follows: as the first sentence in each stimulus pair was always spoken in Standard Dutch, and all 128 sentences were randomized and counterbalanced across in all four conditions across all participants, it may be assumed that the first sentences did not differ systematically across conditions. Activation differences between conditions could therefore only be caused by the different patterns of neural suppression after presentation of the second sentence per condition, that is, be due to an interaction between an overall suppression effect and the speaker or accent variation present in the second sentences.

Four events of interest were identified and entered into a subject-specific General Linear Model, consisting of the 32 stimulus pairs per condition (SS, DS, DA, and DSDA). All onsets within these events were modeled with a length equaling the duration of the both sentences presented and started at the onset of the first sentence in a stimulus pair. Parameter estimates were calculated for each voxel, and contrast maps were constructed for each participant. Finally, the statistical model also considered six separate covariates describing the head-related movements (as estimated by the spatial realignment procedure).

Linear-weighted contrasts were used to specify four contrasts. The conditions SS, DS, DA, and DSDA were analyzed in an 2 × 2 factorial design with accent and speaker as factors. A switch of accent occurred in DA and DSDA, a switch of speaker in DS and DSDA, while SS was associated with neither a switch of accent or speaker. We determined main effects of each factor and the interaction term. A main effect of processing a switch of accent was assessed by $(DA + DSDA) - (SS + DS)$, a main effect of processing a switch of speaker was assessed by $(DS + DA) - (SS + DA)$, and the interaction term by $(SS + DSDA) - (DS + DA)$.

The statistical thresholding of the second-level activation maps associated with these three contrasts was an uncorrected threshold of $P < 0.001$ in combination with a minimal cluster extent of 80 voxels. This yields a whole-brain alpha of $P < 0.05$, determined using a Monte-Carlo

TABLE III. Activation for peaks separated by at least 8 mm for the contrasts (*DA* + *DSDA*) − (*SS* + *DS*) (switch of accent only), (*DS* + *DSDA*) − (*SS* + *DA*) (switch of speaker only)

Structure	Hemisphere	*X*	*Y*	z	*T*-value	*Z*-value
(*DA* + *DSDA*) − (*SS* + *DS*)						
Posterior STG/SMG	Left	−54	40	4	5.91	5.29
Posterior STG/PT	Left	−60	−34	8	4.76	4.41
Posterior MTG	Left	−60	−26	−4	4.10	3.87
Posterior STG/SMG	Right	60	−32	2	6.10	5.43
POp/PG	Left	−50	12	24	4.04	3.81
POp/FOC	Left	−46	16	12	3.97	3.75
POp/PTr	Left	−46	16	12	3.50	3.35
Posterior STG/MTG/SMG	Right	54	−26	−2	5.07	4.65
Anterior STG/TP/MTG	Right	54	4	−16	4.87	4.49
Central opercular cortex	Right	38	18	26	4.36	4.08
	Right					
(*DS* + *DSDA*) − (*SS* + *DA*)						
LOC/OP	Left	−26	−92	32	4.77	4.41
LOC	Left	−26	−76	24	4.12	3.88
LOC	Right	14	−66	66	5.47	4.96
Precuneus/LOC/SPL	Right	12	−58	60	4.32	4.05
Precuneus	Right	6	−52	50	4.06	3.83
MFG	Right	46	24	46	5.02	4.67
MFG/FP	Right	40	36	42	3.72	4.54

Coordinates in MNI standard space. FOC, frontal opercular cortex; FP, frontal pole; LOC, lateral occipital cortex; MFG, middle frontal gyrus; MTG, middle temporal gyrus; PG, precentral gyrus; POp, pars opercularis; PT, planum temporale; PTr, pars triangularis; SMG, supramarginal gyrus; SPL, superior parietal lobule; TP, temporal pole.

Simulation with 1,000 iterations, using a function implemented in Matlab [Slotnick et al., 2003].

RESULTS

Behavioral Results

For each participant, the proportion of correct responses was calculated for the after-task. A response was correct whenever the participant had pressed the button and the sentence had been present in the main experiment, or whenever the participant had not pressed the button and the sentence had not been present in the main experiment. Participants correctly detected whether a sentence was present (or not) on average for 79.2% (SD 10.1%; range, 60.7–96.4%) of the sentences, which are significantly higher than chance level (50%), $t(17) = 12.142$, $P < 0.05$. All individual participants' scores were significantly higher than chance level ($P < 0.05$). Given that all participants could judge whether a sentence had been present in the main experiment above chance level, it seems plausible that participants paid attention to the sentences played in the scanner in the main experiment.

Accent

We assessed which cortical regions showed an effect when a switch of accent was present, versus no switch, (*DA* + *DSDA*) − (*SS* + *DS*). The coordinates of the peak voxels for these effects are listed in Table III and displayed in Figure 2. The peak of the relative increase in BOLD signal for a switch of accent was located in posterior STG bilaterally extending to the ventral supramarginal gyrus (SMG) and left PT. The activation appears more widespread on the left. A second cluster is found in left inferior frontal gyrus (IFG), in pars opercularis (POp), extending into pars triangularis.

We ensured that the activations in left posterior STG/PT for the contrasts (*DA* + *DSDA*) − (*SS* + *DS*) were located in PT using the probability map in Westbury et al. [1999]. The group peak activation results in Figure 2 for (*DA* + *DSDA*) − (*SS* + *DS*) in left posterior STG/PT (−60, −34, 8) is inside the 25–45% probability area, after conversion from MNI to Talairach coordinates [Talairach and Tournoux, 1988], which was necessary to use the Westbury et al. [1999] probability map.

Speaker

We assessed which cortical regions showed an effect when a switch of speaker was present, versus no switch, (*DS* + *DSDA*) − (*SS* + *DA*) (cf. Table III and Fig. 2). Peaks for a relative increase in BOLD for a switch of speaker were located in lateral occipital cortex bilaterally, right precuneus, and right middle frontal gyrus extending into frontal pole. Activations appeared to be more right-lateralized. Finally, no activated clusters were found at the

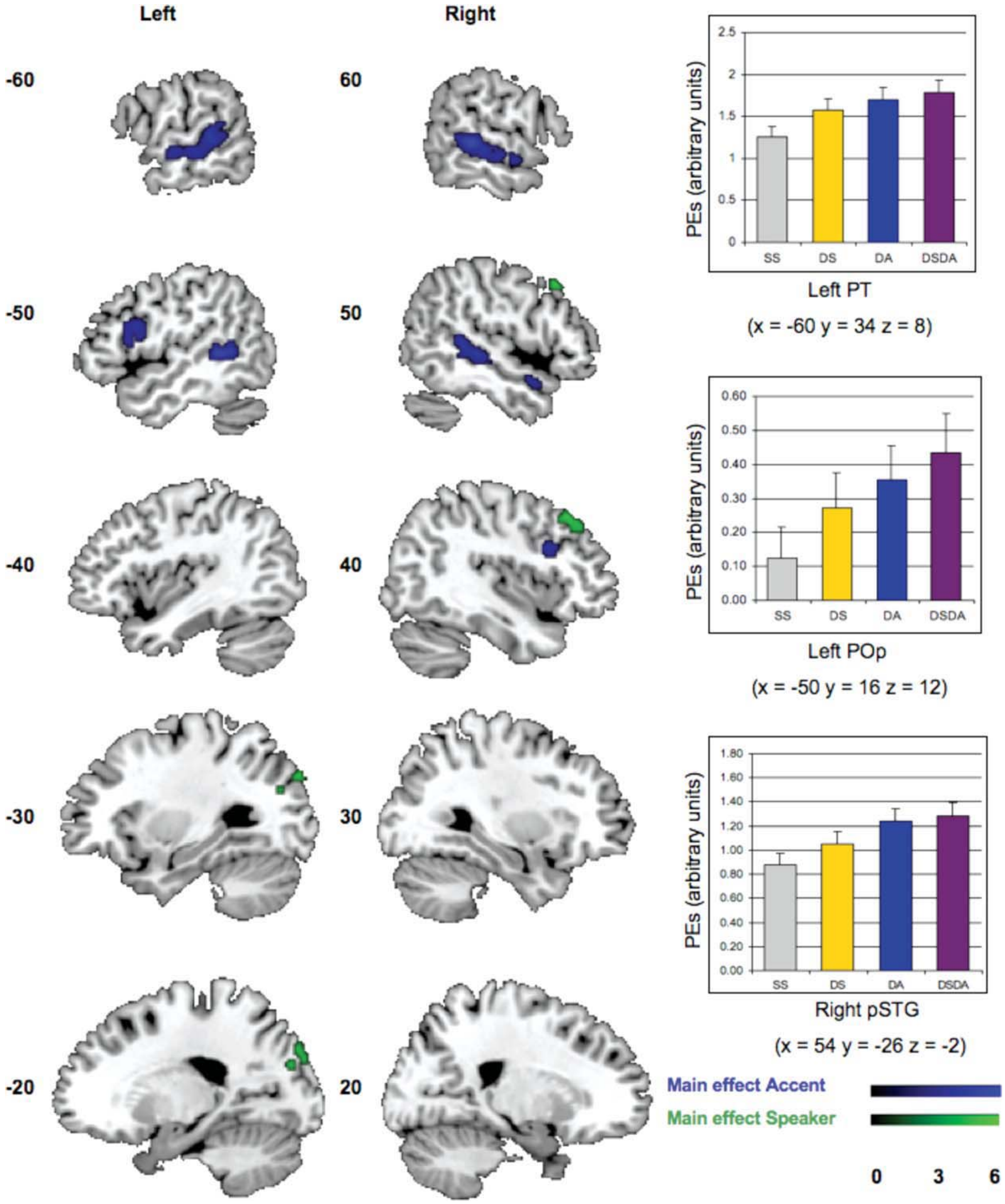

Figure 2.

Main effect for a switch of accent only (*DA* + *DSDA*) − (*SS* + *DS*) in blue, a switch of speaker (*DS* + *DSDA*) − (*SS* + *DA*) in green. Depiction of the brain activation in arbitrary units for the peak voxels in left planum temporale (PT), right superior temporal gyrus (pSRG), and left pars opercularis (POp). The different conditions are colour coded: yellow (SS), orange (DS), blue (DA), and purple (DSDA). The parameter estimates were based on a 10-mm sphere around the peak activation and extracted using the MarsBaR toolbox within SPM5 [Brett et al., 2002].

selected significance level for the interaction term (*SS* + *DSDA*) − (*DS* + *DA*).

DISCUSSION

The present study aimed to establish the neural bases of processing variation in spoken sentences related to speaker and accent in general and to investigate the role of PT in processing accent variation. Specifically, it was hypothesized that BOLD-activity in PT would vary as a result of an increase in accent-related phonetic/phonological variation in the speech signal.

Accent

Several areas in the temporal lobes, including anterior and posterior STG, PT. and SMG, and in the frontal lobes, including POp, showed a relative increase whenever there was a switch of accent present: (*DA* + *DSDA*) − (*SS* + *DS*).

Bilateral STG has been associated with different cognitive functions. Left pSTG (including PT) is generally regarded as part of a pathway for processing comprehensible speech [Davis and Johnsrude, 2003; Poldrack et al., 2001], and it has been suggested that it serves as an interface between the perception and long-term representation in mental lexicon of familiar words [Wise et al., 2001] and is implicated in resolving semantic ambiguities in spoken sentence comprehension [Rodd et al., 2005].

Earlier studies demonstrate that (left) POp [Blumstein et al., 2005; Burton, 2001; Burton et al., 2000; Golestani et al., 2002; Myers, 2007; Wilson and Iacoboni, 2006; Zatorre et al., 1996] as well as posterior STG/PT [Callan et al., 2004; Warren et al., 2005; Wilson and Iacoboni, 2006] is associated with phonetic-analytic listening to speech sounds or syllables. In addition, POp has previously been associated with disambiguation tasks at a syntactic processing level [Fiebach et al., 2004] and has been named as a key structure in models for processing phonetic/phonological variation in speech comprehension [Callan et al., 2004; Skipper et al., 2006]. Furthermore, left POp has been associated with implicit phonemic analysis processes in speech comprehension [Burton et al., 2000], and it may be expected that processing accented speech may rely in part on increased (low-level) auditory analysis of the speech signal.

We also found activations in left SMG for a switch in accent. SMG shows sensitivity to phonological changes in speech [Dehaene-Lambertz et al., 2005]. It has been suggested [Obleser and Eisner, 2009] that SMG has access to abstract (i.e., normalised) phonological units. Activations in SMG in speech perception tasks are thus in many cases interpreted as reflecting involvement in phonological working memory (e.g., [Jacquemot et al., 2003].

Speaker

We found several areas that showed a relative increase when a switch of accent was present for the contrast (*DA* + *DSDA*) − (*SS* + *DS*). These activations included a relative increase in areas in lateral occipital cortex bilaterally, right precuneus, and right middle frontal gyrus extending into frontal pole. These results are generally in line with earlier studies investigating neural activation related to the speaker's voice. Stevens [2004] and Belin et al. [2000] found increases in BOLD activation in MFG for processing voice variation versus nonvocal stimuli. Belin et al. [2000] and Kriegstein and Giraud [2004] both report activations in the precuneus for processing voices.

Nevertheless, most studies on processing speaker variation report more extensive activations in predominantly right-lateralized temporal areas. Studies on processing speaker-related information show a wide variety in the neural locus of this process; some report activation in an area close to the left temporal pole in left anterior STS [Belin and Zatorre, 2003], while others report that perceptual normalization for the speaker occurs in the superior/middle temporal gyri bilaterally and the superior parietal lobule bilaterally [Wong et al., 2004]. Furthermore, a recent repetition–suppression study on spoken sentence processing also does not report whole-brain effects for switching between speakers [Dehaene-Lambertz et al., 2006]. Dehaene-Lambertz et al. [2006] report a small normalization effect for speaker differences in left STG, after applying a more sensitive analysis. It seems plausible that the differences between our results and the aforementioned studies arise both from differences in task. Moreover, previous studies did not explicitly control for regional accent differences between speakers. The present study shows predominantly activations outside the temporal regions when accent differences between speakers are accounted for. Therefore, it could be the case that accent differences between speakers used in previous studies could have affected results, especially in temporal areas.

Speaker and Accent Normalization

The question arises whether phonological and phonetic variation in speech is processed in the same way as speech stimuli that have been distorted or degraded, for instance, by presenting sentences at a lower signal-to-noise ratio [Zekveld et al., 2006] or by noise-vocoding [Obleser et al., 2007]. Relatively few studies investigate the specific effect of different types of distortion of the speech signal and identified areas that are involved more when the intelligibility decreases. Only one study addresses this question in-depth [Davis and Johnsrude, 2003]. Davis and Johnsruhe evaluated the effect of three types of distortions (speech in noise, noise-vocoded speech, and segmented speech) on speech processing. They found that left STG and left IFG became more active for distorted versus intelligible speech. However, activity in left posterior STG varied dependent on the type of distortion, while left anterior STG's responses were form-independent (i.e., showed elevated activation independent from the type of distortion used). It is at this point not feasible to determine whether accented speech and distorted speech are processed differently in left posterior STG, as Davis and Johnsruhe did not include accented speech and our study did not include distorted speech.

CONCLUSION

We conclude that bilateral posterior STG (including PT) and POp are involved in processing various types of distortions in the speech signal. However, further study is required to establish whether these areas differentiate between various types of speech-*intrinsic* (such as accent, speech rate, or clarity of speech) and speech-*extrinsic* variation (such as added noise).

Finally, our results provide further evidence for the hypothesis that PT is associated with processing accent and speaker variation during spoken language comprehension and thus support the theory [Griffiths and Warren, 2002; Warren et al., 2005] that PT serves as a computational hub for processing spectrotemporal variation in auditory perception.

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APPENDIX

TABLE AI. Sentences from the SRT corpus before and after conversion

Sentence no.	Standard Dutch	Novel accent of Dutch
1	De bal vloog over de schutting	De baal vlog offer de schuuttieng
2	Morgen wil ik maar één liter melk	Moorgen wiel iek mar èn litter meelk
3	Deze kerk moet gesloopt worden	Desse keerk mut geslopt woorden
4	De spoortrein was al gauw kapot	De sportreen waas aal goew kaappoot
5	De nieuwe fiets is gestolen	De niwwe fits ies gestollen
6	Zijn manier van werken ligt mij niet	Zeen mannir vaan weerken liegt mee nit
7	Het slot van de voordeur is kapot	Het sloot vaan de vordur ies kaappoot
8	Dat hotel heeft een slechte naam	Daat hotteel heft ŉ sleechte nam
9	De jongen werd stevig aangepakt	De joongen weerd steffig angepaakt
10	Het natte hout sist in het vuur	Het naatte hoet siest ien het vur
11	Zijn fantasie kent geen grenzen	Zeen faantassih keent gèn greenzen
12	De aardappels liggen in de schuur	De ardaappels liegen ien de schur
13	Alle prijzen waren verhoogd	Aalle preezen warren verhogt
14	Zijn leeftijd ligt boven de dertig	Zeen lèfteed liegt boffen de deertieg
15	Het dak moet nodig hersteld worden	Het daak mut noddieg heersteeld woorden
16	De kachel is nog steeds niet aan	De kaachel ies noog stèds nit an
17	Van de viool is een snaar kapot	Vaan de vij-jol ies ŉ snar kaappoot
18	De tuinman heeft het gras gemaaid	De tuunmaan heft het graas gemajt
19	De appels aan de boom zijn rijp	De aappels an de bom zeen reep
20	Voor het eerst was er nieuwe haring	Vor het erst waas eer niwwe harrieng
21	Het loket bleef lang gesloten	Het lokkeet blef laang geslotten
22	Er werd een diepe kuil gegraven	Eer weerd ŉ dippe koel gegraffen
23	Zijn gezicht heeft een rode kleur	Zeen geziecht hèft ŉ rodde klur
24	Het begon vroeg donker te worden	Het beggoon vrug doonker te woorden
25	Het gras was helemaal verdroogd	Het graas waas hèllemal verdrogt
26	Spoedig kwam er een einde aan	Spuddieg kwaam eer ŉ eende an
27	Ieder half uur komt hier een bus langs	Idder haalf ur koomt hir ŉ buus laangs
28	De bel van de voordeur is kapot	De beel vaan de vordur ies kaappoot
29	De wind waait vandaag uit het westen	De wiend wajt vaandag uut het weesten
30	De slang bewoog zich door het gras	De slaang bewog ziech dor het graas
31	De kamer rook naar sigaren	De kammer rok nar siggarren
32	De appel had een zure smaak	De aappel haad ŉ zurre smak
33	De trein kwam met een schok tot stilstand	De treen kwaam meet ŉ schook toot stielstaand
34	De koeien werden juist gemolken	De kujjen weerden juust gemoolken
35	Het duurt niet langer dan een minuut	Het durt nit laanger daan ŉ minnut
36	De grijze lucht voorspelt regen	De greeze luucht vorspeelt règgen
37	Hij kon de hamer nergens vinden	Hee koon de hammer neergens vienden
38	Deze berg is nog niet beklommen	Desse beerg ies noog nit bekloommen
39	De bel van mijn fiets is kapot	De beel vaan meen fits ies kaappoot
40	De auto heeft een lekke band	De oetoh hèft ŉ leekke baand
41	Het moeilijke werk bleef liggen	Het muj-leekke weerk blef lieggen
42	Het vliegtuig vertrekt over een uur	Het vligtuug vertreekt offer ŉ ur
43	De jongens vechten de hele dag	De joongens veechten de hèlle daag
44	De schoenen moeten verzoold worden	De schunnen mutten verzold woorden
45	In de krant staat vandaag niet veel nieuws	Ien de kraant stat vaandag nit vèl niws
46	Door de neus ademen is beter	Dor de nus addemmen ies better

TABLE AI. (Continued)

Sentence no.	Standard Dutch	Novel accent of Dutch
47	Het kind was niet in staat te spreken	Het kiend waas nit ien stat te sprekken
48	De witte zwaan dook onder water	De wiette zwan dok oonder watter
49	Hij nam het pak onder zijn arm	Hee naam het paak oonder zeen aarm
50	Gelukkig sloeg de motor niet af	Geluukkieg slug de mottor nit aaf
51	De leraar gaf hem een laag cijfer	De lèrrar gaaf heem ŉ lag seeffer
52	Het huis brandde tot de grond toe af	Het huus braande toot de groond tuh aaf
53	De foto is mooi ingelijst	De fotto ies moi iengeleest
54	Mijn broer gaat elke dag fietsen	Meen brur gat eelke daag fitsen
55	Een kopje koffie zal goed smaken	Een koopje kooffih zaal gud smakken
56	De schrijver van dit boek is dood	De schreeffer vaan diet buk ies dot
57	Zij heeft haar proefwerk slecht gemaakt	Zee heft har prufweerk sleecht gemakt
58	De sigaar ligt in de asbak	De siggar liegt ien de aasbaak
59	De appelboom stond in volle bloei	De aappelbom stoond ien voolle bluj
60	Er wordt in dit land geen rijst verbouwd	Eer woordt ien diet laand gèn reest verbuwd
61	Hij kan er nu eenmaal niets aan doen	Hee kaan eer nuh ènmal nits an dun
62	De kleren waren niet gewassen	De klerren warren nit gewaassen
63	Het gedicht werd voorgelezen	Het gediecht weerd vorgelèssen
64	Haar gezicht was zwart van het vuil	Har geziecht waas zwaart vaan het vuul
65	De letters stonden op hun kop	De leetters stoonden oop huun koop
66	De groene appels waren erg zuur	De grunne aappels warren eerg zur
67	In het gebouw waren vier liften	Ien het geboew warren vir lieften
68	Lopen is gezonder dan fietsen	Loppen ies gezoonder daan fitsen
69	Het lawaai maakte hem wakker	Het lawwai makte heem waakker
70	Mijn buurman heeft een auto gekocht	Meen burmaan heft ŉ oetoh gekoocht
71	Als het flink vriest kunnen we schaatsen	Aals het flienk frist kuunnen we schatsen
72	De kast was een meter verschoven	De kaast waas ŉ metter verschoffen
73	Oude meubels zijn zeer in trek	Oede mubbels zeen zèr ien treek
74	De portier ging met vakantie	De poortir gieng meet vaakkaantih
75	De lantaarn gaf niet veel licht meer	De laantarn gaaf nit vèl liecht mer
76	Door zijn snelheid vloog hij uit de bocht	Door zeen sneelheed vlog hee uut de boocht
77	Het is hier nog steeds veel te koud	Het ies hir noog steds vèl te koed
78	De oude man was kaal geworden	De oede maan waas kal gewoorden
79	De bomen waren helemaal kaal	De bommen warren hèllemal llemal kal
80	Rijden onder invloed is strafbaar	Reedden oonder ienvlud ies straafbar
81	Onze bank geeft vijf procent rente	Oonze baank geft veef prosseent reente
82	Het verslag in de krant is kort	Het verslaag ien de kraant ies koort
83	In de vijver zwemmen veel vissen	Ien de veeffer zweemmen vel viessen
84	Honden mogen niet in het gebouw	Hoonden moggen nit ien het geboew
85	Een flinke borrel zal mij goed doen	Een flienke boorrel zaal mee gud dun
86	Gisteren waaide het nog harder	Giesteren wajde het noog haarder
87	Het meisje stond lang te wachten	Het meesje stoond laang te waachten
88	De volgende dag kwam hij ook niet	De voolgende daag kwaam hee ok nit
89	Het geschreeuw is duidelijk hoorbaar	Het geschrew ies duudeleek horbar
90	Eindelijk kwam de trein op gang	Eendeleek kwaam de treen oop gaang
91	De grote stad trok hem wel aan	De grotte staad trook heem weel an
92	De bus is vandaag niet op tijd	De buus ies vaandag nit oop teed
93	Onze dochter speelt goed blokfluit	Oonze doochter spèlt gud blookfluut
94	Ook in de zomer is het hier koel	Ok ien de zommer ies het hir kul
95	Zij moesten vier uur hard werken	Zee musten vir ur haard weerken
96	Niemand kan de Fransman verstaan	Nimmaand kaan de Fraansmaan verstan
97	Eiken balken zijn erg kostbaar	Eeken baalken zeen eerg koostbar
98	Het aantal was moeilijk te schatten	Het antaal waas muujleek te schaatten
99	Er waaide een stevig briesje	Er waj-de ŉ stèffieg brisje
100	De vis sprong een eind uit het water	De vies sproong ŉ eend uut het watter
101	Iedereen genoot van het uitzicht	Idderèn genot vaan het uutziecht
102	Het regent al de hele dag	Het règgent aal de hèlle daag
103	Het tempo was voor hem veel te hoog	Het teempoh waas vor heem vèl te hog

TABLE AI. (Continued)

Sentence no.	Standard Dutch	Novel accent of Dutch
104	In juni zijn de dagen het langst	Ien junnih zeen de daggen het laangst
105	De bakkers bezorgen vandaag niet	De baakkers bezoorgen vaandaag nit
106	Het licht in de gang brandt nog steeds	Het liecht ien de gaang braandt noog steds
107	De wagen reed snel de berg af	De waggen red sneel de beerg aaf
108	Lawaai maakt je op den duur doof	Lawai makt je oop deen dur dof
109	In de kerk wordt mooi orgel gespeeld	Ien de keerk woordt moi oorgel gespèld
110	De schaatsen zijn in het vet gezet	De schatsen zeen ien het veet gezeet
111	Toch lijkt me dat een goed voorstel	Tooch leekt mee daat ŉ gud vorsteel
112	Hij probeerde het nog een keer	Hee probbèrde het noog ŉ kèr
113	De zak zat vol oude rommel	De zaak zaat vool oede roommel
114	Zij werd misselijk van het rijden	Zee weerd miesselleek vaan het reedden
115	Door zijn haast maakte hij veel fouten	Dor zeen hast makte hee vèl foeten
116	De nieuwe zaak is pas geopend	De niwwe zak ies paas ge-oppend
117	Dat is voor hem een bittere pil	Daat ies vor heem ŉ biettere piel
118	Op het gras mag men niet lopen	Oop het graas maag meen nit loppen
119	Steile trappen zijn gevaarlijk	Steelle traappen zeen gevarleek
120	De zon gaat in het westen onder	De zoon gat ien het weesten oonder
121	De hond blafte de hele nacht	De hoond blaafte de hèlle naacht
122	De kat van de buren is weg	De kaat vaan de burren ies weeg
123	De trein vertrekt over twee uur	De treen vertreekt offer twe ur
124	Het was heel stil in de duinen	Het waas hel stiel ien de duunnen
125	Hij rookte zijn sigaret op	Hee rokte zeen siggarreet oop
126	De rivier trad buiten haar oevers	De riffir traad buutten har uffers
127	De jongen ging er gauw vandoor	De joongen gieng eer goew vaandor
128	Moeizaam klom de man naar boven	Mujzam kloom de maan nar boffen
129	*De biefstuk is vandaag erg mals*	*De bifstuuk ies vaandaag eerg maals*
130	*De kat likt het schoteltje leeg*	*De kaat liekt het schotteltje lèg*

Sentences 1–128 were presented in the fMRI experiment.