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PET imaging of cochlear-implant and normal-hearing subjects listening to speech and nonspeech

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Abstract

Functional neuroimaging with positron emission tomography (PET) was used to compare the brain activation patterns of normal-hearing (NH) with postlingually deaf, cochlear-implant (CI) subjects listening to speech and nonspeech signals. The speech stimuli were derived from test batteries for assessing speech-perception performance of hearing-impaired subjects with different sensory aids. Subjects were scanned while passively listening to monaural (right ear) stimuli in five conditions: Silent Baseline, Word, Sentence, Time-reversed Sentence, and Multitalker Babble. Both groups showed bilateral activation in superior and middle temporal gyri to speech and backward speech. However, group differences were observed in the Sentence compared to Silence condition. CI subjects showed more activated foci in *right* temporal regions, where lateralized mechanisms for prosodic (pitch) processing have been well established; NH subjects showed a focus in the *left* inferior frontal gyrus (Brodmann's area 47), where semantic processing has been implicated. Multitalker Babble activated auditory temporal regions in the CI group only. Whereas NH listeners probably habituated to this multitalker babble, the CI listeners may be using a perceptual strategy that emphasizes 'coarse' coding to perceive this stimulus globally as speechlike. The group differences provide the first neuroimaging evidence suggesting that postlingually deaf CI and NH subjects may engage differing perceptual processing strategies under certain speech conditions.

Keywords

Imaging; Cochlear implant; Positron emission tomography; Speech perception; Language; Deaf

1. Introduction

Functional brain imaging has rapidly emerged as a tool for exploring the functional anatomy of the living human brain while subjects are actively performing higher brain functions (Posner and Raichle, 1994). Over the last decade, functional neuroimaging into language processing has identified a number of distinct cortical regions and their functional roles in phonological and semantic processing (for review, see Petersen and Fiez, 1993). A few

positron emission tomography (PET) imaging studies have been performed on profoundly deaf subjects using a cochlear-implant (CI) device to hear with the aim of determining a cortical basis that may underlie the wide range of speech performance known to exist among device users (Ito et al., 1990; Herzog et al., 1991; Naito et al., 1995). Speech stimuli activated the *left* temporo-parietal language regions (e.g., Wernicke's area) beyond the primary and secondary auditory cortices in postlingually deaf CI listeners with some speech-recognition abilities. Moreover, when different groups of CI users were compared to the normal-hearing listening to speech, similar brain activation patterns were observed in postlingually deaf CI and normal-hearing subjects; in contrast, prelingually deaf CI users who demonstrated relatively poor speech scores showed little activation in the auditory association areas (Naito et al., 1997).

A major objective of this PET imaging study was to compare the patterns of cortical activation of normal-hearing (NH) with CI subjects listening to different samples of speech stimuli. Specifically, the speech stimuli were obtained from some of the test batteries used for assessing and tracking the speech-perception performance of hearing-impaired subjects using different sensory aids (Kirk et al., 1997). On the basis of these behavioral measures, only postlingually deaf adults demonstrating some open-set abilities were selected for the CI group in this pilot PET study. Both the NH and CI groups were imaged while passively listening to monaurally presented speech or speechlike stimuli of varying complexity: real words, meaningful sentences, sentences played backward, and multitalker babble. We hypothesized that group differences in the brain activation patterns would be evident under these different speech conditions. Group differences would suggest that CI and NH subjects process speech sounds differently. Group differences may also provide insights into the nature of the processing strategies that implant listeners use to enhance speech perception without the benefit of inputs from other sensory modalities (e.g., vision, lip-reading). Some of these results were initially presented in abstract form (Wong et al., 1996).

2. Materials and methods

2.1. Subjects

Five adults (three females, two males; mean age 38.4 ± 5.7 (S.D.) years) with normal-hearing sensitivity comprised the NH group. Five postlingually deaf adults (three females, two males; mean age of 49 ± 9.7 years) using a surgically implanted device (Nucleus-22, Cochlear Corp., Englewood, CO; Clarion-8, Advanced Bionics, Sylmar, CA) comprised the CI group (Table 1). All of the CI subjects demonstrated some open-set, word-recognition abilities, as reflected in their speech-discrimination scores on the NU-6 word list (Tillman and Carhart, 1994) and CID everyday sentences (Davis and Silverman, 1978). All subjects were right-handed. All subjects provided written informed consent to the experimental protocols of this study (IRB #9308-12) approved by the Institutional Review Board of Indiana University and in accordance with the guidelines of the Declaration of Helsinki.

2.2. Stimuli and task

A tape cassette played sounds at about 75 dB SPL for a total of 3 min in each acoustic condition. Acoustic stimuli were originally recorded onto the tape in 1-s bursts alternating with 1 s of silence (30 stimuli per minute). Stimuli were delivered monaurally by a loudspeaker placed about 18 inches from the *right* ear of a NH subject or the speech processor of a CI subject with a *right*-ear implant. To mimic the monaural-hearing condition found in the CI subjects (all were profoundly deaf in the left ear), the left ears of NH subjects were occluded with E-A-R foam inserts to attenuate sound transmission in this ear by at least 25–30 dB SPL. The speech processors of CI subjects remained switched on

throughout the entire imaging session, i.e., during the scanning period and at intervals between scans.

Each subject was scanned under five conditions: a silent baseline condition when no sounds were presented, and four different experimental conditions during which different acoustic signals were presented. The Word condition consisted of individual words from the Multi-syllabic Lexical Neighborhood Test (e.g., ‘banana’, ‘glasses’, ‘children’) (Kirk et al., 1995). The Sentence condition consisted of everyday common phrases of 2–6 words (e.g., ‘I’m fine’, ‘Open the door’, ‘What did you eat for breakfast?’) (Osberger et al., 1991). The Time-reversed (TR) Sentence condition consisted of the common phrases played backward, which were considered as nonspeech control stimuli. The Multitalker Babble (Auditec, St. Louis, MO) condition consisted of multiple male talkers speaking simultaneously, which is similar to a ‘cocktail-party’ environment. Subjects were instructed to passively listen to the stimuli presented in all four acoustic conditions, and to press a button on alternate stimuli with their *right* thumb to keep the subject’s attention focused on the stimuli. No motor task was required in the silent baseline condition.

2.3. PET image acquisition and processing

PET scans were obtained using a Siemens 951/31R system, which produced 31 brain image slices at an intrinsic spatial resolution of approximately 6.5 mm full-width-at-half-maximum (FWHM) in plane and 5.5 mm FWHM in the axial direction. During the entire imaging session, the subject lay supine with his/her eyes blindfolded. Head movement was restricted by placing the subject’s head on a custom-fit, firm pillow, and by strapping his/her forehead to the imaging table, allowing pixel-by-pixel within-subject comparisons of cerebral blood flow (CBF) across task conditions. A peripheral venipuncture and an intravenous infusion line were placed in the subject’s left arm. For each condition, about 50 mCi of $H_2^{15}O$ was injected intravenously as a bolus; upon bolus injection, the scanner was switched on for 5 min to acquire a tomographic image (during acoustic condition, sounds were played over a 3-min period followed by 2 min of silence). A rapid sequence of scans was performed to enable the selection of a 90 s time window beginning 35–40 s after the bolus arrived in the brain. For each condition, instructions were given immediately prior to scanning. Five scans were acquired for each subject for the following stimulus conditions: (1) Silent Baseline, (2) Word, (3) Sentence, (4) TR Sentence, (5) Multitalker Babble.

The following six paired-image subtractions were then performed on averaged group data to reveal statistically significant results in the difference images: Word–Baseline, Sentence–Baseline, Multitalker Babble–Baseline, TR Sentence–Baseline, Sentence–Word, Sentence–TR Sentence. The Sentence–Word subtraction isolated processing of suprasegmental cues in speech beyond those for processing single words (e.g., cues signaling sentence-level comprehension, syntax). In the Sentence–TR Sentence, nonspeech is subtracted from speech. Regions of significant brain activation were identified by performing an analysis process (Michigan software package, Minoshima et al., 1993) that included image registration, global normalization of the image volume data, identification of the intercommissural (anterior commissure–posterior commissure) line on an intrasubject-averaged PET image set for stereotactic transformation and alignment, averaging of subtraction images across subjects, and statistical testing of brain regions demonstrating significant regional CBF changes. Changes in regional CBF were mapped onto a standardized coordinate system of Talairach and Tournoux (1988). Foci of significant CBF changes were tested by the Hammersmith method (Friston et al., 1990, 1991) and values of P 0.05 (one-tailed, corrected) were deemed statistically significant.

3. Results

3.1. Foci of significant blood flow increases

In the speech (word or sentence) minus baseline subtractions, both the NH and CI groups showed CBF increases at multiple foci in the superior temporal gyrus (STG) of both sides of the brain (Fig. 1A). The STG foci are typically in the vicinity of the superior temporal sulcus, which separates the superior from the middle temporal gyrus (MTG). These foci were found over a wide anterior to posterior distance relative to the anterior commissure. These foci were arbitrarily grouped into different parts of the temporal region: anterior (y -5), middle (y from -5 to -23), and posterior (y from -24 to -35).

In the Word minus Baseline subtraction, the NH group showed CBF increases in the posterior STG on the left (Table 2: focus #1) and a homologous region on the right (Table 2: focus #2); a middle focus was also found in the MTG on the right (Table 2: focus #3). The CI group showed more activated foci, especially in the left temporal region. These activated foci in the STG/MTG were located in the anterior (Table 2: focus #7) toward Brodmann's area (BA) 38, middle (Table 2: focus #8), and posterior (Table 2: focus #5) parts. On the right, a focus was found in the anterior STG (Table 2: focus #6) and in the STG near or bordering the secondary auditory area (BA 42) (Table 2: focus #4).

In the Sentence minus Baseline subtraction, the NH group showed multiple foci of CBF increases in the STG and/or MTG from anterior (Table 2: foci #12, 13) to middle (Table 2: foci #9, 10) temporal regions. The left inferior frontal gyrus (BA 47) (Table 2: focus #14) also showed a CBF increase (Fig. 1B). In the right temporal region, only one focus in the MTG (BA 21) showed a CBF increase that reached statistical significance. The CI group showed CBF increases in the middle to posterior part of the left temporal region, in the STG/MTG typically near the superior temporal sulcus (Table 2: foci #16, 18). In contrast to the NH group, the CI group showed multiple foci of CBF increases in the right temporal regions, from anterior (Table 2: focus #15) to such middle parts as the primary auditory cortex (BA 41) in the transverse temporal gyrus, secondary auditory area (BA 42), and a more ventrolateral focus in the STG/MTG (Table 2: foci #17, 19, 20).

In the Multitalker Babble minus Baseline subtraction, only the CI group showed CBF increases in the temporal regions of both sides (Fig. 1C). On the left side, the anterior (Table 2: focus #24) and the posterior (Table 2: focus #21) foci in the STG were separated by over 30 mm. On the right side, the two temporal regions bordered or were ventrolateral to the secondary auditory area (BA 42) (Table 2: foci #22, 23).

In the TR Sentence minus Baseline, the NH group showed CBF flow increases in the STG/MTG of both sides (Table 2: foci #25–27). The CI group showed CBF increases only on the left cortical side in an anterior and posterior focus of the STG/MTG (Table 2: foci #28, 29).

In the Sentence minus Word subtraction, a CBF increase was found only in the *left* inferior frontal gyrus (BA 47) (Table 2: focus #31) similar to the focus found in the Sentence minus Baseline subtraction. In the Sentence minus TR Sentence subtraction, a single CBF increase was found for the NH [right supramarginal gyrus (BA 40); (Table 2: focus #32)] and CI [right MTG (BA 21); (Table 2: focus #33)] groups.

3.2. Foci of significant blood flow decreases

In the baseline subtractions for the speech stimuli, the NH group showed CBF decreases in the precuneus (BA 7) and/or posterior cingulate gyrus (BA 31, 23, 30) (Table 3: foci #2, 5, 8), whereas the CI group showed decreases in the lingual gyrus (BA 18) (Table 3: foci #4,

- 9). CBF decreases included those in or near the medial frontal lobe [subcallosal gyrus (Table 3: focus #3); rectus gyrus (Table 3: foci #6, 10)].

4. Discussion

4.1. Patterns of cortical activation : implications of group differences on the nature of speech processing

The NH and CI groups showed bilateral activation of STG to monaural stimuli, whether the stimuli were speech (sentence, word) or complex nonspeech (TR sentence). This finding confirms other recent imaging studies of NH subjects in which the STG is activated bilaterally by both speech and complex nonspeech sounds, regardless of the semantic content (meaningfulness) of the stimuli or the type of cognitive task required (Howard et al., 1992; Binder et al., 1997).

The foci activated in the auditory temporal regions were generally more robust and greater in number in the CI than NH group for the baseline subtractions. The fewer number of peak activations in the NH group may be related to habituation to the stimuli, whether speech or 'speechlike' during passive listening. This is evident in the Word compared to Baseline condition where the NH group showed fewer activated foci than the CI group, to isolated, although novel words, especially in the *left* STG/MTG. In contrast, the CI group showed more widespread activation in the left temporal region. CI subjects may process and encode speech as degraded signals, and often presume such signals as speech on the basis of a 'coarse' coding of the input signal (Shipman and Zue, 1982). This perceptual coding strategy may reflect CI listeners engaging auditory processing more extensively, possibly in an attempt to interpret degraded and ambiguous acoustic stimuli, especially when listening to isolated words without benefit of other auditory cues from a larger context (Koch et al., 1996). The subjects were not informed of the type of acoustic stimuli used prior to each scan, although they were informed at the beginning of the PET session that scans would be obtained using speech and nonspeech signals.

The group difference in the strength and number of activated foci may, in part, also be due to the fact that the 'silent' resting baseline condition was not exactly identical for the two groups. Both groups were exposed to the same background noise in the PET-imaging room. Although the acoustic thresholds of CI users are typically between 25 and 35 dB HL (K. Kirk, personal communication), these thresholds are somewhat elevated compared to those in normal-hearing subjects (0–20 dB HL is considered normal; Goodman, 1965). CI subjects can easily detect speech at conversational levels, as well as the background noise (~65 dB SPL) in the imaging room (including scanner noise). The continuous white noise associated with the PET environment is considerably quieter than the very loud, scanner noise generated during functional magnetic resonance imaging (e.g., see Ravicz et al., 1997). Thus, it is unlikely that the background-noise stimulation would differ appreciably for the two groups in the baseline (silent) condition to fully account for the larger differences observed in the baseline subtractions for the CI than NH group in similar regions.

The meaningful sequences of words in the Sentence condition convey both syntactic and suprasegmental information beyond the lexical information found in isolated words: semantic (e.g., sentence-level comprehension) and prosodic. For the NH group, the activation observed in the more ventral part of the *left* inferior frontal gyrus (BA 47) for both the Sentence–Word and Sentence–Baseline subtractions is consistent with the role that this frontal region plays in some aspects of semantic processing (Fiez, 1997). Although these subtractions would suggest that this region may contribute to sentence-level comprehension, it is unclear why a similar frontal focus did not reach statistical significance in the Sentence–TR Sentence subtraction. Even though the TR sentences were clearly devoid of any

semantic content, and hence these stimuli were originally chosen for the nonspeech control condition, it is noteworthy that NH subjects did report that such complex auditory patterns contained features resembling a foreign language that they did not understand. Regardless of the nature of the semantic processing, similar processing strategies at the sentence level was not evident in the CI group, since no activation in BA 47 was found in this group for any of the subtractions involving the Sentence condition.

The two groups may also have differentially processed prosodic information at the sentence level. Pitch processing in the NH group would be consistent with activation of the STG on the right, where lateralized hemispheric mechanisms underlying this type of prosodic processing have been well-established (Zatorre et al., 1994). However, the extent to which these passive listeners were attending to prosodic cues is unclear, since mere monaural (right ear) stimulation would activate the ipsilateral (right) temporal auditory region. Compared to the NH group, the CI group showed more activated foci in the *right* STG. This finding is perhaps surprising given that a larger temporal activation would be expected on the contralateral (left) cortical side based on the anatomy of the central auditory pathway. The extensive activation in the right STG may reflect a larger role of pitch processing for the CI listeners in the Sentence condition. CI listeners are known to rely heavily on contextual cues (e.g., prosody, syntax, semantics) to enhance their speech-recognition performance (Waltzman et al., 1992). Exploiting the processing of this type of suprasegmental information contained in the sentence may be a critical perceptual strategy in processing these signals. Moreover, the more extensive right temporal activation may, in part, be due to a greater computational demand imposed on the CI group relative to the NH group by merely listening to sentences. This interpretation is consistent with recent neuroimaging findings suggesting that the extent of activation in the right temporal region is modulated by the complexity of sentence-comprehension tasks (Just et al., 1996).

Multitalker babble compared to baseline did not reveal any statistically significant activation in the temporal region for the NH group. This finding may simply reflect habituation by these passive listeners to ‘cocktail-party’ stimuli, despite the fact that they can readily recognize this cacophony of sounds as speech from the outset. Surprisingly, multitalker babble was effective in activating the temporal auditory region bilaterally in CI listeners. Apparently, the CI listeners recognized multitalker babble sufficiently as speechlike. The activation in the temporal region involving the secondary auditory cortex (BA 42) suggests that an earlier cortical stage or lower-level processing may be engaged for processing this signal more as a complex acoustic signal with some speechlike features than as simply meaningful speech. The speech stimuli in this study have consistently activated foci at or near the STG/MTG junction for both CI and NH groups. Thus, the activation pattern observed in CI listeners for multitalker babble is consistent with an account emphasizing ‘coarse’ coding (e.g., recognizing words using broad phonetic categories ; Shipman and Zue, 1982) used to perceive multitalker babble globally as speechlike in nature.

Both groups failed to show significant activation in the anterior cingulate gyrus for any of the subtractions. This region in the medial frontal cortex was typically activated in other studies involving active-task conditions, and was likely related to attentional mechanisms (Posner and Petersen, 1990). Thus, the current observations are consistent with the passive-listening conditions used in which subjects attended minimally to the stimulus by button pressing on alternate stimuli. Since the button pressing was not based on any phonetic or lexical decisions, it was also not unexpected that Broca’s area (BA 44, 45) would not be activated by speech stimuli. This frontal language area is typically engaged in imaging studies when an overt (explicit) phonetic decision is required for speech stimuli (e.g., Zatorre et al., 1996; Gandour et al., 1998).

4.2. Cortical regions of de-activation

Recent analysis of PET imaging studies, using both auditory and non-auditory tasks, have revealed common areas showing blood flow decreases, regardless of task (Shulman et al., 1997; Binder et al., 1998). Both groups in the present study showed similar foci of de-activation in the speech conditions compared to baseline : NH in precuneus, posterior cingulate gyrus, medial frontal cortex (subcallosal gyrus), and left inferior temporal cortex (fusiform gyrus); CI in an extrastriate visual cortical area (BA 18). Given that such regions of de-activation were observed across different tasks, Shulman et al. (1997) proposed that the processing demands in active-task conditions were sufficient to suspend ongoing processes (e.g., unconstrained verbal thought processes, monitoring of the external environment or body image) found in the resting baseline condition. In the present study, such processes would likely occur in the baseline condition, and to some degree in the acoustic conditions since the subjects were passively listening to acoustic stimuli with only button pressing to alternate stimuli.

4.3. Conclusion

The present functional neuroimaging study compared the brain activation patterns of CI with NH subjects listening to different samples of speech and complex nonspeech stimuli. Although a group comparison was performed in another PET study using sentences as the only speech condition, that study generally concluded that postlingually deaf CI and NH subjects employ similar cortical mechanisms for speech recognition (Naito et al., 1997). The present study, however, provides the first neuroimaging evidence to suggest that postlingually deaf CI users with some open-set speech abilities may engage cortical speech-processing strategies that differ from those used by NH subjects. CI users may rely heavily on suprasegmental information contained in speech stimuli beyond isolated words to interpret the complex signals from their prosthesis. Moreover, as CI users learn to use their device and develop some speech discrimination abilities, the brain reorganization induced in these monaural perceivers may be guided in a manner similar to that suggested in patients with unilateral deafness (no implant). For example, a recent functional brain imaging study revealed that monaural pure-tone stimulation in monaurally deaf patients evoked an auditory-cortical activation distributed more bilaterally rather than strongly contralaterally as found in normal-hearing subjects (Scheffler et al., 1998). In the CI subjects of the present study, the greater ipsilateral (right) temporal-cortical activation, observed at least in the Sentence condition, may also reflect a fundamental shift in hemispheric activation induced by auditory experience solely in one ear.

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References

- Binder JR, Frost JA, Hammeke TA, Cox RW, Rao SM, Prieto T. Human brain language areas identified by functional magnetic resonance imaging. *J Neurosci.* 1997; 17:353–362. [PubMed: 8987760]
- Binder JR, Frost JA, Hammeke TA, Bellgowan PSF, Rao SM, Cox RW. Conceptual processing during rest: an account of task-induced deactivation. *NeuroImage.* 1998; 7:S380.
- Davis, H.; Silverman, SR. *Hearing and Deafness.* 4. Holt, Rhinehart, and Winston; New York: 1978.

- Fiez JA. Phonology, semantics, and the role of the left inferior prefrontal cortex. *Hum Brain Mapping*. 1997; 5:79–83.
- Friston K, Frith C, Liddle P, Dolan R, Lamerstma A, Frackowiak R. The relationship between global and local changes in PET scans. *J Cereb Blood Flow Metab*. 1990; 10:458–466. [PubMed: 2347879]
- Friston K, Frith C, Liddle P, Frackowiak R. Comparing functional PET images: The assessment of significant changes. *J Cereb Blood Flow Metab*. 1991; 11:81–95.
- Gandour J, Wong D, Hutchins G. Pitch processing in the human brain is influenced by language experience. *NeuroReport*. 1998; 9:2115–2119. [PubMed: 9674604]
- Goodman A. Reference zero levels for pure-tone audiometer. *ASHA*. 1965; 7:262–263.
- Herzog H, Lamprecht A, Kuhn A, Roden W, Vosteen KH, Finendegen LE. Cortical activation in profoundly deaf patients during cochlear implant stimulation demonstrated by H₂ ¹⁵O PET. *J Comput Assist Tomogr*. 1991; 15:369–375. [PubMed: 1851187]
- Howard D, Patterson K, Wise R, Brown WD, Friston K, Weiller C, Frackowiak R. The cortical localization of the lexicon. *Brain*. 1992; 115:1769–1782. [PubMed: 1486460]
- Ito J, Sakakibara J, Honjo I, Iwasaki Y, Yonekura Y. Positron emission tomographic study in a patient with a cochlear implant. *Arch Otolaryngol Head Neck Surg*. 1990; 116:1437–1439. [PubMed: 2248748]
- Just MA, Carpenter PA, Keller TA, Eddy WF, Thulborn KR. Brain activation modulated by sentence comprehension. *Science*. 1996; 274:114–116. [PubMed: 8810246]
- Kirk KI, Pisoni DB, Osberger MJ. Lexical effects on spoken-word recognition by pediatric cochlear implant users. *Ear Hear*. 1995; 16 (5):470–481. [PubMed: 8654902]
- Kirk KI, Pisoni DB, Miyamoto RC. Effects of stimulus variability on speech perception in listeners with hearing impairment. *JSLHR*. 1997; 40:1395–1405. [PubMed: 9430759]
- Koch DB, Carrell TD, Tremblay K, Kraus N. Perception of synthetic syllables by cochlear-implant users: Relation to other measures of speech perception. *Assoc Res Otolaryngol*. 1996; 19:104.
- Minoshima S, Koeppe R, Mintum M, Berger KL, Taylor SF, Frey KA, Kuhl DE. Automated detection of the intercommissural line for stereotaxic localization of functional brain imaging. *J Nucl Med*. 1993; 34:322–329. [PubMed: 8429356]
- Naito Y, Okazawa H, Honjo I, Hirano S, Takahashi H, Shiomi Y, Hoji W, Kawano M, Ishizu K, Yonekura Y. Cortical activation with sound stimulation in cochlear implant users demonstrated by positron emission tomography. *Cogn Brain Res*. 1995; 2:207–214.
- Naito Y, Okazawa H, Hirano S, Takahashi H, Kawano M, Ishizu K, Yonekura Y, Konishi J, Honjo I. Sound induced activation of auditory cortices in cochlear implant users with post- and prelingual deafness demonstrated by positron emission tomography. *Acta Oto-Laryngol*. 1997; 117:490–496.
- Osberger MJ, Robbins AM, Miyamoto RT, Berry SW, Myres WA, Kessler KS, Pope ML. Speech perception abilities of children with cochlear implants, tactile aids, or hearing aids. *Am J Otol*. 1991; 12:105–115. [PubMed: 2069171]
- Petersen SE, Fiez JA. The processing of single words studied with positron emission tomography. *Annu Rev Neurosci*. 1993; 16:509–530. [PubMed: 8460901]
- Posner M, Petersen SE. The attention system of the human brain. *Annu Rev Neurosci*. 1990; 13:25–42. [PubMed: 2183676]
- Posner, MI.; Raichle, ME. *Images of Mind*. W.H. Freeman; New York: 1994.
- Ravicz ME, Melcher JR, Talavage TM, Benson RR, Rosen BR, Kiang NYS. Characterization and reduction of imager-generated noise during functional magnetic resonance imaging. *Assoc Res Otolaryngol*. 1997; 20:205.
- Scheffler K, Bilecen D, Schmid N, Tschopp K, Seelig J. Auditory cortical responses in hearing subjects and unilateral deaf patients as detected by functional magnetic resonance imaging. *Cereb Cortex*. 1998; 8:156–163. [PubMed: 9542894]
- Shipman DW, Zue VW. Properties of large lexicons: Implications for advanced isolated word recognition systems. *Proc IEEE Conf Acoustics, Speech, Signal Processing*. 1982:546–549.

- Shulman GL, Fiez JA, Corbetta M, Buckner RL, Miezin FM, Raichle ME, Petersen SE. Common blood flow changes across visual tasks: II. Decreases in cerebral cortex *J Cogn Neurosci*. 1997; 9:648–663.
- Talairach, J.; Tournoux, P. 3-Dimensional Proportional System: An Approach to Cerebral Imaging. Thieme Medical; New York: 1988. Co-planar Stereotaxic Atlas of the Human Brain.
- Tillman, TW.; Carhart, R. Northwestern University Auditory Test No. 6. Technical Report No. SAMTR-66-55. USAF School of Aerospace Medicine, Brooks AFB Base; TX: 1994. An expanded test for speech discrimination utilizing CNC monosyllabic words.
- Waltzman SB, Cohen NL, Fisher SG. An experimental comparison of cochlear implant systems. *Semin Hear*. 1992; 13:195–207.
- Wong D, Sehgal M, Learn J, Pisoni DB, Miyamoto RT, Hutchins G, Yune H. Activation of auditory cortex with speech stimuli in cochlear implant subjects: a positron emission tomography (PET) study. *Assoc Res Otolaryngol*. 1996; 19:107.
- Zatorre RJ, Evans AC, Meyer E. Neural mechanisms underlying melodic perception and memory for pitch. *J Neurosci*. 1994; 14:1908–1919. [PubMed: 8158246]
- Zatorre RJ, Meyer E, Gjedde A, Evans AC. PET studies of phonetic processing of speech: review, replication, and reanalysis. *Cereb Cortex*. 1996; 6:21–30. [PubMed: 8670635]

Fig. 1.

Averaged PET images showing statistically significant foci of activation and de-activation to speech and speechlike stimuli. A: Word– Baseline: bilateral activation of the superior and middle temporal gyri in NH (left) and CI (right) groups. A focus of de-activation (green) is shown for both groups (see Table 3 for details). Horizontal sections at 2 mm below (left) and at the bicommissural plane (right). B: Sentence– Baseline: activation of the ventral part of the *left* inferior frontal gyrus (BA 47) in the NH group. Coronal section at 35 mm anterior to the anterior commissure. C: Multitalker Babble–Baseline: bilateral activation of the superior temporal gyrus in the CI group. Coronal section at 33 mm posterior to the anterior commissure showing the secondary auditory cortex (BA 42). The left side of the brain is shown on the left (L) of all PET images.

Table 1

Cochlear-implant subjects: clinical profile and speech-recognition performance

Patient	Gender	Age (years)	Etiology of deafness	Profound deafness (duration in years)	CI device (No. of electrodes)	Implant use (years)	Speech recognition	
							NU-6 words (%)	CID sentences (%)
1. R.O.	F	47	Progressive SNHL	7	Nucleus-22	8	60	98
2. L.M.	M	51	Meniere's disease	3	Nucleus-22	3	50	97
3. M.N.	M	36	Meningitis	2	Nucleus-22	3	20	83
4. E.S.	F	63	Progressive SNHL	17	Clarion-8	2	68	85
5. M.G.	F	48	Progressive SNHL	3	Clarion-8	1	42	72

SNHL, sensorineural hearing loss.

Table 2

Foci of significant blood flow increases^a

Normal hearing					Cochlear implant						
Region	Brodmann's area	Coordinates (mm)			Z score	Region	Brodmann's area	Coordinates (mm)			Z score
		x	y	z				x	y	z	
Word-Baseline											
1. L Superior temporal gyrus	22	-55	-24	2	5.6	4. R Superior temporal gyrus	22/42	55	-22	4	6.2
2. R Superior/middle temporal gyrus	22/21	62	-26	2	4.6	5. L Middle temporal gyrus	21	-60	-33	4	6.0
3. R Middle temporal Gyrus	21	57	-8	-7	4.4	6. R Superior temporal gyrus	22	46	5	-4	5.7
						7. L Superior temporal gyrus	22	-48	-1	-4	5.6
						8. L Superior/middle temporal gyrus	22/21	-57	-13	0	5.1
Sentence-Baseline											
9. L Middle temporal gyrus	21	-57	-13	-2	5.2	15. R Superior/middle temporal gyrus	38, 21/22	51	3	-7	6.1
10. L Superior temporal gyrus	22/21	-55	-17	0	5.2	16. L Superior/middle temporal gyrus	21/22	-57	-35	4	5.8
11. R Middle temporal gyrus	21	60	-8	-7	4.7	17. R Superior/middle temporal gyrus	22/21	53	-8	-2	5.2
12. L Middle temporal gyrus	21	-48	3	-11	4.6	18. L Superior temporal gyrus	22	-57	-19	2	5.0
13. L Middle temporal gyrus	21	-51	-4	-11	4.6	19. R Superior/ transverse temporal gyrus	22/41	46	-13	-2	4.3
14. L Inferior frontal gyrus	47	-44	35	-16	4.5	20. R Superior temporal gyrus	22/42	53	-22	4	4.2
Multitalker Babble-Baseline											
						21. L Superior temporal gyrus	22/42	-57	-33	7	6.3
						22. R Superior temporal gyrus	42/22	53	-19	4	6.2
						23. R Superior temporal gyrus	22	51	-6	-2	5.5
						24. L Superior temporal gyrus	22	-46	1	-7	4.6
Time-reversed Sentence-Baseline											
25. L Superior temporal gyrus	22	-57	-24	4	5.1	28. L Middle temporal gyrus	21	-60	-31	4	5.7
26. L Superior temporal gyrus	22/21	-53	-8	-2	5.1	29. L Superior temporal gyrus	22	-48	3	-2	4.7
27. R Middle temporal gyrus	21	57	-8	-4	5.0	30. R Cerebellum	-	37	-53	-20	4.2
Sentence-Word											
31. L Inferior frontal gyrus	47	-46	37	-16	4.2						
Sentence-Time-reversed Sentence											
32. R Supramarginal gyrus	40	42	-49	40	4.4	33. R Middle temporal gyrus	21	53	1	-9	4.3

^gSignificant activation foci that exceed the Hammersmith statistical criterion of significance (adjusted P -threshold=0.05) in normalized CBF for all subtractions. Stereotaxic coordinates, in millimeters, are derived from the human brain atlas of Talairach and Tournoux (1988). The x -coordinate refers to medial-lateral position relative to midline (negative=left); y -coordinate refers to anterior-posterior position relative to anterior commissure (positive=anterior); z -coordinate refers to superior-inferior position relative to the CA-CP (anterior commissure–posterior commissure) line (positive=superior). Designation of Brodmann's areas is also based on this atlas. L=left; R=right.

Table 3

Foci of significant blood flow decreases^a

Normal hearing					Cochlear implant						
Region	Brodmann's area	Coordinates (mm)			Z score	Region	Brodmann's area	Coordinates (mm)			Z score
		x	y	z				x	y	z	
Word-Baseline											
1. Cerebellum	–	1	–51	4	–5.1	4. R Lingual gyrus	18	8	–82	–4	–5.2
2. Precuneus	7/31	1	–49	36	–4.4						
3. L Subcallosal gyrus	25	–8	19	–11	–4.2						
Sentence-Baseline											
5. Posterior cingulate gyrus/Precuneus	31/7	3	–49	40	–4.5	9. Lingual gyrus	18	6	–80	–4	–4.2
6. Rectus gyrus	11	–1	19	–22	–4.4						
7. L Fusiform gyrus	36/20	–30	–37	–16	–4.2						
8. Posterior cingulate gyrus	23/30	–6	–53	18	–4.2						
Multitalker Babble-Baseline											
10. Rectus gyrus	11	–3	30	–25	–4.5						
11. L Optic tract	–	10	1	–11	–4.2						
Time-reversed Sentence-Baseline											
						12. L Middle temporal gyrus	21/37	–62	–53	–4	–4.3
Sentence-Word											
13. Anterior cingulate gyrus	32	1	14	34	–4.5						

^a Significant de-activation foci that exceed the Hammersmith statistical criterion of significance (adjusted P -threshold=0.05) in normalized CBF for all subtractions. See footnote in Table 2 regarding Talairach stereotaxic coordinates and Brodmann's areas.