Speech Perception in MRI Scanner Noise by Persons with Aphasia

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Abstract

Purpose. To examine reductions in performance on auditory tasks by aphasic and neurologically-intact individuals as a result of concomitant MRI scanner noise.

Methods. Four tasks together forming a continuum of linguistic complexity were developed. They included complex-tone pitch discrimination, same/different discrimination of minimal pair syllables, lexical decision, and sentence plausibility. Each task was performed by persons with aphasia (PWA) and by controls. The stimuli were presented in silence and also in the noise recorded from within the bore of a 3T MRI scanner at three signal-to-noise ratios (S/Ns).

Results. Across the four tasks, the PWA scored lower than the controls and performance fell as a function of decreased S/N. However, the rate at which performance fell was not different across the two listener groups in any task.

Conclusions. Depending upon the relative levels of the signals and noise, the intense noise accompanying MRI scanning has the potential to severely disrupt performance. However, PWA are no more susceptible to the disruptive influence of this noise than are unimpaired individuals usually employed as controls. Thus, fMRI data from aphasic and control individuals may be interpreted without complications associated with large interactions between scanner noise and performance reduction.

MeSH Keywords: Speech Perception, Aphasia, Magnetic Resonance Imaging, Noise

Introduction

Functional Magnetic Resonance Imaging (fMRI) is a technique that is increasingly being applied in the study of brain-behavior relationships. An indirect measure of brain activity, fMRI quantifies changes in blood-oxygen concentration to estimate localized increases in neuronal activity. It is commonly assumed that task performance during fMRI testing is reflective of performance outside the scanning environment. Thus, brain activity measured using fMRI is thought to mirror ‘real life’ neurological processing. However, it is quite possible that this is not always the case; especially in populations with neurological impairment, where the scanning environment itself may negatively influence task performance and, concomitantly, affect brain function.

One of the most obvious aspects of the scanning environment involves the intense noise associated with gradient switching during image acquisition. The noise associated with MRI can reach levels as high as 130 to 140 dB SPL at 3T (Foster, Hall, Summerfield, Palmer, & Bowtell, 2000; Ravicz, Melcher, & Kiang, 2000). Although progress is being made toward decreasing the intensity of the noise produced by MRI scanners, these are generally design considerations not under the control of the experimenter. However, several methods do exist for limiting noise exposure during scanning, which is especially important when auditory stimuli are incorporated into the fMRI task. The signal to noise ratio (S/N) during fMRI can be improved by raising the acoustic stimulus intensity. However, because the level of the signal cannot be safely raised above approximately 90 dB SPL, much of this effort is directed toward attenuating the ambient noise. Earplugs or earphones are commonly employed, but these devices cannot protect against bone-conducted noise and provide no more than 40 dB of attenuation even when used in combination (Ravicz et al., 2000).

Another technique employed to limit the influence of scanner noise involves "sparse" imaging (Fridriksson & Morrow, 2005; Hall et al., 1999). Unlike conventional fMRI, in which acquisition of each full volume image of the brain is repeated without pause, sparse fMRI separates the two- to three-second acquisition periods by several seconds. These periods, during which scanner noise is absent, may then be used for stimulus presentation. This technique is possible as the increase in oxygenated hemoglobin lags behind stimulus presentation by several seconds. Although it allows the presentation of acoustic stimuli in relative quiet, sparse imaging is not without limitations. In particular, the number of brain volume acquisitions is considerably reduced within a scanning session of a given duration. Reviews provided by Amaro et al. (2002) and by Moelker and Pattynama (2003) provide comprehensive descriptions of the various sources of acoustic noise in MR imaging and descriptions of experimental paradigms employed to limit the influence of this noise.

Much of the work examining the influence of acoustic scanner noise has been directed toward its ability to produce activation of particular brain regions. The intense noise can cause problems for the study of auditory perception or language because it produces activation in brain regions associated with auditory processing (Bandettini, Jesmanowicz, Van Kylen, Birn, & Hyde, 1998; Bilecen, Radu, & Scheffler, 1998; Hall et al., 2000; Shah, Jäncke, Grosse-Ruyken, & Müller-Gärtner, 1999).

However, the possibility also exists for the intense ambient noise to produce changes in task performance. This is a particular concern when fMRI is used to study brain function in persons with aphasia (PWA), as decreased task performance by aphasic individuals in the presence of competing auditory stimuli has been reported. Indeed, the use of fMRI to study the processing defects in aphasia has increased dramatically in recent years (cf., Price & Crinion, 2005). Although sparse fMRI design has been used in several of these studies (e.g. Fridriksson & Morrow, 2005; Fridriksson, Morrow, Moser, Fridriksson, & Baylis, in press; Fridriksson, Morrow, Moser & Baylis, in press; Martin et al., 2005) continuous scanning techniques are usually employed.

Murray, Holland, and Beeson (1997) found reductions in auditory comprehension in the presence of competing pure tone or speech stimuli when the task involved attention to one signal in the presence of another (focused attention) or when the task required active monitoring of both signals (divided attention). These same authors (1998) found that the reduction in utterances produced under divided attention relative to isolation was greater for PWA than for normal controls. Murray (2000) also found decreased word retrieval and pure tone discrimination by aphasic persons compared to normal controls on both focused and divided attention tasks employing pure-tone competing stimuli. Indeed, it has been suggested that the language-processing deficits in PWA are strongly associated with these general limitations in attention or resource allocation (McNeil & Kimelman, 1986; McNeil, Odell, & Tseng, 1991).

In light of these findings, the use of continuous fMRI scanning might potentially be troublesome when using auditory stimuli to modulate brain activity in PWA. Because substantial noise levels are usually present at the level of participants’ ears, any fMRI study, regardless of the stimuli utilized to modulate brain function, involves data collection in the presence of a pulsating background noise. Given that almost all previous fMRI studies of aphasia have used continuous scanning, and that this trend is likely to continue in future research, it is imperative to understand to what extent scanner noise influences auditory task performance in PWA.

The purpose of the current study was to determine the extent to which the intense noise accompanying MRI scanning can serve as a distracter to both neurologically-intact and aphasic individuals, by examining reductions in performance on auditory tasks as a result of concomitant noise. Specifically, it was examined whether MRI noise affects performance of PWA to a greater extent than it does the performance of normal control participants. This performance was examined in a series of tasks spanning a large portion of the linguistic continuum. Across these tasks, performance was assessed in silence and also in the presence of scanner noise at three S/N ratios.

Method

Participants

Sixteen native English-speaking listeners participated. One group consisted of eight PWA who were recruited from the University of South Carolina Speech & Hearing Center (see Table 1). All PWA had incurred a left hemisphere stroke and were at least 6 months post-onset. Their ages ranged from 41 to 70 years, with a mean of 57 years. Five of the eight participants were women and all were right-handed. The mean level of education for this group was 15 years (ranging from 11-22 years). A group of eight control subjects also served. These individuals were matched for age within two years of their counterpart with aphasia. All participants had pure-tone audiometric thresholds of

20 dB HL or better at octave frequencies from 250 to 4000 Hz (ANSI, 1996). The exception was one PWA who had a threshold of 30 dB HL at 4000 Hz in one ear.

Table 1 about here

Stimuli

A set of four auditory tasks was designed. In the first task, listeners judged whether a pair of complex tones had the same or different pitch. In the second, listeners judged whether two monosyllabic nonsense words were the same or different. In the third task, listeners performed lexical decisions for words and non-words, and in the fourth, listeners judged the plausibility of short sentences.

Task 1. Complex-tone Frequency Discrimination. Stimuli for the first task were created by synthesizing the first 20 harmonics at equal amplitude. The first tone in the pair always had a 200-Hz fundamental frequency. Following a 500-ms interstimulus interval, a second tone was presented with a fundamental frequency of either 200 Hz (same pair), or three, six, or nine Hz above or below 200 Hz (for a total of six different pairs). Each tone burst was 700 ms in duration, including 10-ms onset and offset ramps, to match the average duration of the syllable pairs in task two. Further, the spectrum of each tone burst was shaped using a digital 1/3-octave filter bank (composed of thirty 1000-order FIR bandpass filters) to match the long-term average amplitude spectrum of the speech items in task two.

Task 2. Minimal-Pair Syllable Discrimination. For this task, nonsense syllables were drawn from the Same-Different Discrimination section (subtest 1) of the Psycholinguistic Assessments of Language Processing in Aphasia (PALPA; Kay, Lesser, & Coltheart, 1992). Forty minimal pairs were selected. Syllable pairs for "same" trials were generated by repeating the first word in each pair. The 40 same pairs and 40 different pairs were equally divided into four sub-lists. These lists were approximately balanced for position of the contrast (initial or final phoneme) and phonetic content. An additional four pairs served as practice stimuli. Lists of the speech stimuli employed are presented in the Appendix.

Task 3. Lexical Decision. For this task, 40 words and 40 non-words were taken from the Auditory Lexical Decision section (subtest 5) of the PALPA. Real words were selected from the low imagery portion of the test to match the lack of imagery elicited by the non-words. The stimuli were divided into four lists of 10 words and 10 non-words each and the lists were approximately balanced for number of syllables and phonological complexity. An additional four words and four non-words served as practice stimuli.

Task 4. Sentence Plausibility. For this task, simple three-word sentences were created using concrete, frequently occurring, high-imagery words. Forty plausible and 40 implausible sentences were created. Half the sentences were of the form [subject-verb-direct object] and the other half were [subject-verb-adjective]. They were divided into four lists of 10 plausible and 10 implausible sentences and were balanced for direct object versus adjective construction, and approximately balanced for number of syllables and phonetic content. An additional two plausible and two implausible sentences served as practice stimuli.

Scanner Noise Recording. A recording from within the bore of a 3T Philips Intera fMRI scanner was used as the noise signal. The procedures employed to record the scanner noise followed those of Foster et al. (2000). The interested reader is directed there for details on this procedure and the substantial safety issues involved when recording in the presence of the strong magnetic field. Briefly, the recording was made by fixing a non-ferrous microphone (Brüel&Kjær 4165) connected to a shielded and non-ferrous extension cable (Brüel&Kjær 0128) in the position of the left ear aligned with the axis of the scanner bore. The microphone was connected using this cable to a preamplifier and sound level meter (Brüel&Kjær 2235) located outside the scanning room, and the output waveform from the sound level meter was recorded digitally using a high-quality D/A converter at 44 kHz sampling and 16 bit resolution. To allow the opportunity for accurate future measurements, the signal generated by a sound level meter calibrator (Brüel&Kjær 4230) was also recorded at the same gain settings as a reference signal.

The waveform and spectrum of the noise recorded within the bore of the scanner is displayed in Figure 1. An echo planar (EPI) sequence was employed with the following specifics: TR=4 s, TE=44 ms, Matrix=3.25x3.25x5 mm, SENSE=2. The noise had a pulsatile waveform that repeated every 65 ms and an amplitude spectrum having a peak at roughly 400 Hz that fell at a rate of roughly 12 dB/octave out to approximately 10 kHz. The noise had an RMS level that measured 95 dBA with a peak level of 107 dBA.

Figure 1 about here

Stimulus Preparation The speech items for tasks two through four were produced by a professional male speaker having a standard American dialect. Recordings were made within an audiometric booth using a condenser microphone having a flat frequency response (AKG C2000B). The signal was preamplified (Mackie 1202VLZ) and digitally recorded (Echo Gina 24) at a sampling rate of 48 kHz with 16 bit resolution.

Each individual tone burst or speech item, as well as the scanner noise, was digitally scaled to the same RMS level. To create the signal-in-noise stimuli for each of the tasks, the signals were attenuated by the appropriate amount and mixed with the scaled scanner noise to yield S/N ratios of -6, -12, and -18 dB. An additional condition in which scanner noise was absent (S/N infinity) was also prepared. To avoid the increased masking that occurs when a signal occurs coincident with the onset of a maker (Zwicker, 1965; Bacon & Healy, 2000), the scanner noise (or silence in the S/N infinity condition) began 1.5 seconds prior to the onset of each signal or signal pair and extended 0.75 seconds following each offset.

To ensure that the relative difficulty of the subset lists of speech items within each task was similar, pilot testing was performed. A group of seven normal-hearing (same 20 dB HL criteria) adults aged 22 to 26 years heard each of the speech items at a S/N of -15 dB. The presentation order of tasks and subsets within each task was randomized for each listener and procedures were the same as those employed in the formal experiment.

It was found that the mean percent correct for each of the four stimulus subsets was within five percent of the grand mean for all the subsets comprising tasks two and four. However, for task three, one of the subsets was found to be substantially less difficult than the other three. To equate the difficulty of these subsets, items were swapped across lists while maintaining the approximate balancing for number of syllables and phonetic content. The percent correct for each of the four revised lists was calculated to be within 2% of the grand mean of these lists.

Procedure

The stimuli were presented using a PC and commercial software, which also collected responses (E-Prime v1.0, Psychology Software Tools, Inc., 2002). The files were converted to analog form (Edirol UA25) and presented diotically over Sennheiser HD 250II headphones. The transduced level at each ear was set to 70 dBA in a flat plate coupler. The four auditory tasks, as well as the four S/N ratios within each task, were heard in a different random order for each participant. In addition, the correspondence between subset list and S/N condition was randomized for each participant. However, this randomization was identical for a given PWA and their corresponding control subject. The listeners heard all the S/N ratios comprising one task before proceeding to the next task. Each speech item in tasks 2 - 4 was presented only once in a different random order for each participant. For task 1, the different-frequency complex tone pairs were each presented twice at each S/N ratio and the same-frequency pair was presented 12 times at each S/N for an equal number of same and different trials.

Each of the four tasks began with a brief practice phase in which the practice speech items or each of the complex tone pairs were presented along with visual feedback on the computer screen consisting of a large green or red circle. The practice stimuli were presented once without masker noise at the beginning of each task, and again with the items appearing at the S/N ratio of the upcoming condition before each S/N condition.

Listeners responded by pressing a large (63 mm diameter) green or red button after each trial. The subsequent trial began two seconds after the response to the prior. Participants had as much time as required to respond and received no feedback during the test phase. Testing took place with the experimenter and the participant seated within an audiometric booth and required a single one-hour session.

The PWA also underwent neuropsychological testing during a separate session to assess overall language and auditory comprehension. This test battery was administered by a speech-language pathologist and included the Western Aphasia Battery (WAB; Kertesz, 1982) and the Revised Token Test (RTT; McNeil & Prescott, 1978). Testing took place in a quiet room with the participant and examiner comfortably seated at a table. The Oral Language Subtests of the WAB were administered to assess language functioning and define the aphasia type and severity. The WAB provides an Aphasia Quotient (AQ), which is an overall language score derived from the following subtest: spontaneous speech, comprehension, naming, and repetition. The RTT was administered to assess auditory comprehension and processing efficiencies. The RTT requires participants to follow a series of verbally-presented directions of varying lengths and complexities utilizing 20 plastic tokens that differ in size, shape, and color.

Results

The results of the behavioral testing of the PWA are shown in Table 1. These individuals displayed a range of aphasia types and severities. Performance on the complex-tone frequency-discrimination task (Task 1) is displayed in Figure 2. Not surprisingly, the PWA performed more poorly than their normal counterparts across all S/N ratios, despite the fact that both groups of subjects had hearing thresholds within normal limits. However, their reduction in performance as a function of scanner noise at poorer S/N ratios was similar to that of the controls. A two-way (2 listener groups x 4 S/Ns) ANOVA with one repeated factor indicated that the main effects of listener group [F(1, 14) = 18.7, p < .001] and S/N were significant [F(3, 42) = 23.5, p < .001]. However, the interaction that would potentially indicate differences across the two listener groups in their response to the presence of scanner noise was not significant [F(3, 42) = 0.7, p = .54].

Performance on the minimal-pair syllable discrimination task (Task 2) is displayed in Figure 3. As in Task 1, performance was poorer for the PWA, and performance for both groups fell as a function of S/N. Apparent from this figure is the remarkable similarity in the rate (slope) at which performance fell across the two groups. As for Task 1, a two-way (2 listeners groups x 4 S/Ns) ANOVA with one repeated factor indicated that the main effects of listener group [F(1, 14) = 23.7, p < .001] and S/N were significant [F(3, 42) = 34.1, p < .001]. Again, the interaction was not significant [F(3, 42) = 0.1 p = .95].

Performance on the lexical decision task (Task 3) is displayed in Figure 4. One of the PWA was unable to complete this task due to fatigue, so data are shown for the remaining seven. Again, performance was poorer for the PWA, and performance for both groups fell as a function of S/N. A two-way (2 listeners groups x 4 S/Ns) ANOVA with one repeated factor indicated that the main effects of listener group [F(1, 13) = 9.1, p < .01] and S/N were again significant [F(3, 39) = 49.7, p < .001]. Although there does appear to be some difference in the rate at which performance fell for the two groups, this difference, if reliable, would indicate that performance of the control subjects was more disrupted by the relative increases in scanner noise. However, this small difference was not significant [F(3, 39) = 2.3 p = .09].

Finally, performance on the sentence plausibility task (Task 4) is displayed in Figure 5. As in all other tasks, performance was poorer for the PWA, and both groups fall as a function of S/N. In accord with the previous analyses, a two-way (2 listener groups x 4 S/Ns) ANOVA with one repeated factor indicated that the main effects of listener group [F(1, 14) = 46.3, p < .001] and S/N were significant [F(3, 42) = 34.1, p < .001], but the interaction was not [F(3, 42) = 1.1 p = .38].

Discussion

Unlike conditions such as cochlear hearing impairment, in which it is well known that auditory reception is especially poor when background noise is present (cf. Moore, 1998), less is known about the influence of cognitive impairment on the perception of speech in noise. This topic is of particular relevance for studies that employ auditory stimulation during fMRI, where high levels of noise exist.

The actual S/N associated with a particular scanning session can be difficult to determine; thus, it was important to investigate performance across a range of S/N values.

Because experiments involving aphasic individuals employ a variety of tasks, it was also important to investigate tasks varying in linguistic content. Perhaps the most reasonable prediction would have been that the noise associated with MRI would serve as a distracter and make any fMRI task a focused-attention task. It would then be anticipated that PWA would perform disproportionately poorer than their neurologically-intact counterparts as competing noise was introduced. This reasonable finding would compromise any fMRI study of aphasia by seriously complicating its interpretation.

Perhaps surprisingly, it was found that performance of the PWA did not fall more steeply than that of their neurologically-intact peers as scanner noise was introduced and as signal levels were decreased relative to the noise. Although their performance in silence was lower in every task, their reductions in performance as a result of scanner noise were remarkably similar to that of the normal controls. These data allow conclusions to be drawn about the influence of scanner noise on tasks ranging from simple pitch discrimination to sentence plausibility. Because the talker, scanner noise recording, and procedures were the same, results across the various tasks may be directly compared. The average difference in performance between listener groups in Tasks 1 to 4 was 17% and this difference held constant within 4% across the tasks. Thus, the influence of scanner noise on performance was remarkably similar across the linguistic continuum. It may be concluded that continuous MRI scanner noise is not a sufficiently disruptive stimulus to produce exaggerated reductions in performance in PWA. Instead, the reduced performance displayed by aphasic individuals may be a result of poorer baseline performance in quiet and the resulting restriction in performance range from this reduced level of proficiency down to chance.

Noise associated with MRI can be dealt with in a number of ways. They involve (1) reducing the intensity of the noise produced by the scanner or transmitted to the bore, (2) introducing active noise cancellation, (3) employing sparse design techniques, and (4) attenuating the noise at the level of the participants' ears.

Progress is being made on the first factors. Noise can be reduced by restricting the mobility (increasing the mass) of the gradient coil. Alternatively, vibration transmission from the coil assembly can be isolated by enclosing it in a vacuum, or by fixing or isolating the coil mounts. These considerations are, of course, only relevant during the design and installation of the scanner, and each can have drawbacks or limitations. Software modifications to existing installations are also possible. Slower ramp times ("smooth gradients") can be effective at reducing noise, but these implementations are limited because of their ability to compromise the quality of MR images. Active noise cancellation systems have been developed to reduce the gradient noise by delivering the ambient noise signal to the ear canal following phase inversion (Chambers et al., 2001). However, the true benefits are limited by the scanner vibrations conducted through the body because cancellation only eliminates the air-conducted sound energy in the ear canal.

The strength of sparse fMRI design is based on the silent periods between volume collections. For example, a noise-filled volume acquisition time (TA) of three seconds and a time between the start of each volume acquisition (TR) of ten seconds, yields a silent interval between TAs of seven seconds. This interval is sufficient for both presentation of stimuli and collection of responses. However, a continuous fMRI sequence with a three-second TR will acquire 200 full brain volumes in ten minutes, whereas a sparse fMRI sequence with a ten-second TR and a three-second TA will acquire only 60 volumes in the same amount of time. This is a major limitation when it comes to measuring the hemodynamic response function (HDR). The HDR describes the gradual increase in the ratio of oxygenated hemoglobin following increased neural activity. Estimation of the HDR is crucial for analyzing fMRI data. Also, several studies have suggested that decreases in time-to-peak of the HDR can reflect improved neurological function. For example, Peck and colleagues (2004) found that decreased time-to-peak in specific regions of interest correlated with improved naming performance in persons with aphasia. If the TR is ten seconds and the rate of stimulus presentation is fixed, the HDR cannot be estimated. Although this problem might be ameliorated by jittering the inter-stimulus interval (Belin, Zatorre, Hoge, Evans, & Pike, 1999), this method would increase the total experimental time to an intolerable length in order to achieve comparable statistical power to that achieved in a relatively-brief continuous sequence. A hybrid scanning sequence that acquires a rapid set of brain volumes, followed by a silent interval (Schwarzbauer et al., 2006) could be used to assess the HDR. But this type of sequence is not readily available without expert re-programming of the scanner software. Thus, although sparse scanning techniques offer substantial advantages, it is clear that continuous scanning is desirable in some situations.

Current efforts toward reducing the influence of scanner noise are largely directed at attenuating the intensity of the noise at the participants' ear. If properly inserted, EAR foam earplugs can provide as much as 40 dB of attenuation. However, detailed measurements have indicated attenuation closer to 25 – 29 dB in the frequency range where most of the gradient noise resides (Ravicz & Melcher, 2001). Because of difficulties associated with the use of earplugs in fMRI studies employing acoustic stimuli, earmuffs are often employed. While the earmuffs tested by Ravicz and Melcher (2001) provided approximately 35 dB of attenuation, measurements performed in our laboratories on other commercially-available circumaural earmuffs have indicated that the attenuation of ambient noise can be far lower. When measured on a flat-plate headphone coupler, attenuation values of 15-25 dB were observed. These values were even lower when tested on a KEMAR acoustic manikin, which provided a poorer seal approximating that between the earmuff and a typical adult human head. Differences in the frequency response of stimulus delivery or noise attenuation can also produce dramatic differences in S/N at particular frequencies.

The current study employed listeners having audiometric thresholds generally within normal limits. Even moderate losses of 40 dB HL can be accompanied by broadened auditory tuning and poor frequency selectivity (cf. Moore, 1998). If the signal is more restricted in frequency than the masker, broad auditory filters have the effect of reducing S/N by encompassing larger amounts of masker energy. It should be noted that many of the potential subjects considered for the current study had moderate to severe hearing losses, which made them ineligible for participation. This should be expected -- both aphasia and presbycusis appear more commonly in older individuals. Although the current results are free of this confound and may be attributed directly to neurological state, this additional complication associated with hearing loss must be considered when testing individuals on auditory tasks in background noise.

Conclusions

The exact specification of S/N in fMRI studies employing auditory stimuli is a complicated matter. However, performance reduction as a result of scanner noise was found to be similar for both aphasic and normal individuals across a wide range of S/N values. Further, this performance reduction, as well as the difference in performance across groups, was found to be relatively constant across tasks varying in linguistic complexity from frequency discrimination of tones (no linguistic content) to sentence plausibility. It is concluded that the PWA employed in this study were no more susceptible than their normal counterparts to the disruptive impact of the intense noise associated with fMRI scanning. These results indicate that aphasic individuals may be compared to their normally-functioning peers on a variety of tasks, in fMRI environments characterized by a range of S/N values, without complications associated with large interactions between scanner noise and performance reduction.

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References:

Amaro, E. Jr., Williams, S.C.R., Shergill, S.S., Fu, C.H.Y., MacSweeney, M., Picchioni, M.M., Brammer, M.J., & McGuire, P.K. (2002). Acoustic noise and functional magnetic resonance imaging: Current strategies and future prospects. Journal of Magnetic Resonance Imaging, 16, 497-510.

ANSI (1996). ANSI-S3.6, 1996, Specifications for audiometers. New York: American National Standards Institute.

Bacon, S.P. & Healy, E.W. (2000). Effects of ipsilateral and contralateral precursors on the temporal effect in simultaneous masking with pure tones. Journal of the Acoustical Society of America, 107, 1589-1597.

Bandettini, P.A., Jesmanowicz, A., Van Kylen, J., Birn, R.M. & Hyde, J.S. (1998). Functional MRI of brain activation induced by scanner acoustic noise. Magnetic Resonance in Medicine, 39, 410-416.

Belin, P., Zatorre, R.J., Hoge, R., Evans, A.C. & Pike, B. (1999). Event-related fMRI of the auditory cortex. NeuroImage, 10, 417-429.

Bilecen, D., Radu, E.W., Scheffler, K. (1998). The MR tomography as a sound generator: fMRI tool for the investigation of the auditory cortex. Magnetic Resonance in Medicine, 40, 934-937.

Chambers, J., Akeroyd, M.A., Summerfield, A.Q. & Palmer, A.R. (2001). Active control of the volume acquisition noise in functional magnetic resonance imaging: Method and psychoacoustical evaluation. Journal of the Acoustical Society of America, 110, 3041-3054.

Foster, J., Hall, D., Summerfield, A. Q., Palmer, A., & Bowtell, R. (2000). Sound-level measurements and calculations of safe noise dosage during EPI at 3T. Journal of Magnetic Resonance Imaging, 12, 157-163.

Fridriksson, J., & Morrow, K. L. (2005). Cortical activation and language task difficulty in aphasia. Aphasiology, 19, 239-250.

Fridriksson, J., Morrow, K. L., Moser, D., Fridriksson, A., & Baylis, G. (in press). Neural correlates of anomia recovery in aphasia. NeuroImage.

Fridriksson, J., Morrow, K. L., Moser, D., & Baylis, G. (in press). Age related variability in cortical activity during language processing. Journal of Speech, Language, and Hearing Research.

Hall, D. A., Haggard, M. P., Akeroyd, M. A., Palmer, A. R., Summerfield, A. Q., Elliott, M. R., Gurney, E. M., & Bowtell, R.W. (1999). "Sparse" temporal sampling in auditory fMRI. Human Brain Mapping, 7(3), 213-223.

Hall, D.A., Summerfield, A.Q., Gonclaves, M.S., Foster, J.R., Palmer, A.R., & Bowtell, R.W. (2000). Time-course of the auditory BOLD response to scanner noise. Magnetic Resonance in Medicine, 43, 601-606.

Kay, J., Lesser, R., & Coltheart, M. (1992). Psycholinguistic Assessments of Language Processing in Aphasia, English Edition. East Sussex, UK: Psychology Press.

Kertez, A. (1982). Western Aphasia Battery. New York: Grune & Stratton.

Martin, P.I., Naeser, M.A., Doron, K.W., Bogdan, A., Baker, E.H., Kurland, J., Renshaw, P., Yurgelun-Todd, D. (2005). Overt naming in aphasia studied with a functional MRI hemodynamic delay design. Neuroimage, 28(1), 194-204.

McNeil, M.R., & Kimelman, M.D.Z. (1986). Toward an integrative information processing structure of auditory comprehension and processing in adult aphasia. In: L.L. LaPointe (Ed.), *Seminars in Speech and Language: Aphasia: Nature and Assessment* (pp. 123-147). New York: Thieme-Stratton, Inc.

McNeil, M.R., Odell, K., & Tseng, C.H. (1991). Toward the integration of resource allocation into a general theory of aphasia. Clinical Aphasiology, 20, 21-39.

McNeil, M.R., & Prescott, T.E. (1978). *Revised token test.* Austin, TX: PRO-ED, Inc.

Moelker, A., & Pattynama, P.M.T. (2003). Acoustic noise concerns in functional magnetic resonance imaging. Human Brain Mapping, 20, 123-141.

Moore, B.C.J. (1998). Cochlear hearing loss. London: Whurr.

Murray, L. L. (2000). The effects of varying attentional demands on the word retrieval skills of adults with aphasia, right hemisphere brain damage, or no brain damage. Brain and Language, 72, 40-72.

Murray, L. L, Holland, A. L., & Beeson, P.M. (1997). Auditory processing in individuals with mild aphasia: a study of resource allocation. Journal of Speech, Language, and Hearing Research, 40, 792-808.

Murray, LL, Holland, AL, Beeson, PM. (1998). Spoken language of individuals with mild fluent aphasia under focused and divided attention conditions. Journal of Speech, Language, and Hearing Research, 41, 213-227.

Peck, K.K., Moore, A.B., Crosson, B.A., Gaiefsky, M., Gopinath, K.S., White, K., & Briggs, R.W. (2004). Functional magnetic resonance imaging before and after aphasia therapy: Shifts in hemodynamic time to peak during an overt language task. Stroke, 35, 554-559.

Price, C.J., & Crinion, J. (2005). The latest on functional imaging studies of aphasic stroke. Current Opinion in Neurology, 18, 429-434.

Ravicz, M. E., Melcher, J. R., & Kiang, N. Y. (2000). Acoustic noise during functional magnetic resonance imaging. Journal of the Acoustical Society of America, 108, 1683-1696.

Ravicz, M. E., & Melcher, J. R. (2001). Isolating the auditory system from acoustic noise during functional magnetic resonance imaging: Examination of noise conduction through the ear canal, head, and body. Journal of the Acoustical Society of America, 109, 216-231.

Schwarzbauer, C., Davis, M.H., Rodd, J.M. & Johnsrude, I. (2006). Interleaved silent steady state (ISSS) imaging: A new sparse imaging method applied to auditory fMRI. NeuroImage, 29, 774-782.

Shah, N.J., Jäncke, L., Grosse-Ruyken, M-L., & Müller-Gärtner, H.W. (1999). Influence of acoustic masking noise in fMRI of the auditory cortex during phonetic discrimination. Journal of Magnetic Resonance Imaging, 9, 19-25.

Zwicker, E. (1965). Temporal effects in simultaneous masking by white noise bursts, Journal of the Acoustical Society of America, 37, 653-663.

Table 1. Characteristics of the aphasic participants

	P1	P2	P3	P4	P5	P6	P7	P8
Age	65	61	70	58	49	46	41	68
Gender	F	M	F	M	M	F	F	F
Education (yrs)	12	22	17	12	11	16	18	12
Post-Onset (yrs)	3	6	2	0.5	2	4	2	13
Classification	Conduction	Broca's	Conduction	Broca's	Anomic	Anomic	Broca's	Anomic
WAB—AQ	77.5	50.7	66.1	38.4	78.0	86	43.4	61.6
RTT	13.20	*	9.75	11.44	12.36	12.80	11.46	12.06

* This individual was unable to complete this test

Figure Captions

Figure 1. Waveform (upper panel) and long-term average amplitude spectrum (lower panel) of the acoustic signal recorded from within the bore of a 3T MRI scanner.

Figure 2. Group mean accuracy and standard errors for participants with aphasia (PWA) and for normal-hearing controls (Cntrl.) on a task involving the identification of complex tone pairs having the same or different frequencies. The signals were presented in silence or in a background of MRI scanner noise at the relative levels indicated. Chance performance is indicated by the dotted line.

Figure 3. Group mean accuracy and standard errors for participants with aphasia (PWA) and for normal-hearing controls (Cntrl.) on a task that required same/different judgments of minimal-pair monosyllabic nonsense words. The signals were presented in silence or in a background of MRI scanner noise at the relative levels indicated. Chance performance is indicated by the dotted line.

Figure 4. Group mean accuracy and standard errors for participants with aphasia (PWA) and for normal-hearing controls (Cntrl.) on a task involving lexical decision of words and non-words. The signals were presented in silence or in a background of MRI scanner noise at the relative levels indicated. Chance performance is indicated by the dotted line.

Figure 5. Group mean accuracy and standard errors for participants with aphasia (PWA) and for normal-hearing controls (Cntrl.) on a task involving the plausibility of short sentences. The signals were presented in silence or in a background of MRI scanner noise at the relative levels indicated. Chance performance is indicated by the dotted line.

Appendix

Task 2: Minimal-Pair Syllable Discrimination

Examples: sɛn / sɛn

dət / dət

bɛp / dɛp

mɪb / mɪm

Different:	Same:
Subset 1:	
təp / dəp	kɛp / kɛp
baun / maun	kaut / kaut
pɛf / bɛf	pɛb / pɛb
sɛf / sɛv	kib / kib
veid / veit	bɪp / bɪp
daib / maib	fɪk / fɪk
ləp / lət	baip / baip
gɛn / gɛm	sauk / sauk

vim / vin

nəf / fəf

kaib / kaib

nəd / nəd

Subset 2:

kib / tib

pɛb / pɛm

bɪp / mɪp

taif / taiv

sət / səp

faib / faim

naup / laup

laib / laip

heip / heib

nap / naf

təp / təp

baun / baun

pɛf / pɛf

faib / faib

saud / saud

nək / nək

nɪs / nɪs

faig / faig

vəl / vəl

puk / puk

Subset 3:

kaut / kaus

fɪk / fɪp

baip / daip

təs / dəs

sɛf / sɛf

veid / veid

daib / daib

taif / taif

saud / taud	sət / sət
nək / nəg	təs / təs
nɪs / lɪs	lɛp / lɛp
gɛb / gɛp	nap / nap
vɪl / vɪn	miv / miv
nɛf / mɛf	fib / fib

<u>Subset 4:</u>

lɛp / lɛk	ləp / ləp
kɛp / kɛb	gɛn / gɛn
sauk / saup	naup / naup
kaib / gaib	laib / laib
nəd / nəz	heip / heip
faig / faid	gɛb / gɛb
vəl / zəl	vɪl / vɪl
puk / tuk	vim / vim
miv / niv	nɛf / nɛf
fib / vib	nəf / nəf

Task 3: Lexical Decision

Examples:

puct, loment, reash, minner, pig, cart, pupil, summer

Nonwords:	Words:
Subset 1:	
andiance	attitude
pitaro	character
drister	miracle
foaster	concept
hetal	effort
vallige	manner
sprool	bonus
plen	thought
afe	clue
fide	fact
Subset 2:	
baranter	idea
halocle	gravity
sogmy	episode

mither	moment
cottee	tribute
stadent	theory
sping	woe
drim	plea
pib	purpose
weast	length

Subset 3:

ragio	quality
epilent	irony
fannel	session
trantor	member
pisture	system
wembow	satire
slape	dogma
prath	realm
hend	mercy
kalt	deed

Subset 4:

tanacco	analogy
biffle	opinion

trabite
mirtage
sammer
slurch
pline
clee
dend
lutter

principle
crisis
folly
valour
thing
pact
wrath
treason

Task 4: Sentence plausibility

Examples:

Eggs drink coffee.   Leaves change color.

Fire is cold.   Cherries are red.

Implausible:	Plausible:
Subset 1:	
Cows read books.	Bread goes stale.
Drums sip tea.	Queens wear crowns.
Rabbits lift weights.	Babies drink milk.
Trees make candles.	People bake food.
Computers eat fish.	Farms have animals.
Music is silent.	Knives are sharp.
Rugs are liquid.	Cliffs are steep.
Metal is wooden.	Ice cream is sweet.
Bananas are pink.	Paper is thin.
Watermelons are rubbery.	Diamonds are expensive.
Subset 2:	
Guns send letters.	Cars use gas.

Fleas jump rope.

Tables eat snow.

Doors keep secrets.

Birds boil potatoes.

People walk dogs.

Pastors give sermons.

Maps give directions.

Kids grow older.

Balls are square.

Pumpkins are blue.

Glass is fluffy.

Sandpaper is smooth.

Rainbows are colorless.

Rocks are hard.

Fire is hot.

Cheetahs are fast.

Water is clear.

Gum is sticky.

<u>Subset 3:</u>

Phones leak oil.

Chickens make bricks.

Pictures write songs.

Nuns wear tutus.

Cabinets grow hair.

People eat food.

Dentists fix teeth.

Squirrels climb trees.

Cups hold liquid.

Hammers pound nails.

Ice is warm.

Sprinters are slow.

Fruit is greasy.

Gasoline is tasty.

Ants are enormous.

Rings are round.

Apples are red.

Water is wet.

Chips are salty.

Sheep are wooly.

Subset 4:

Ears taste food.

Pets wave flags.

Carpets ask questions.

Tires play Bingo.

Books use electricity.

Cows make milk.

Cats chase mice.

Watches keep time.

Children eat cookies.

Factories make cars.

Rain is dry.

Pens are sour.

Air is muddy.

Skyscrapers are tiny.

Cheeseburgers are tasteless.

Juice is liquid.

Slugs are slimy.

Grass is green.

Thunder is loud.

Pillows are soft.

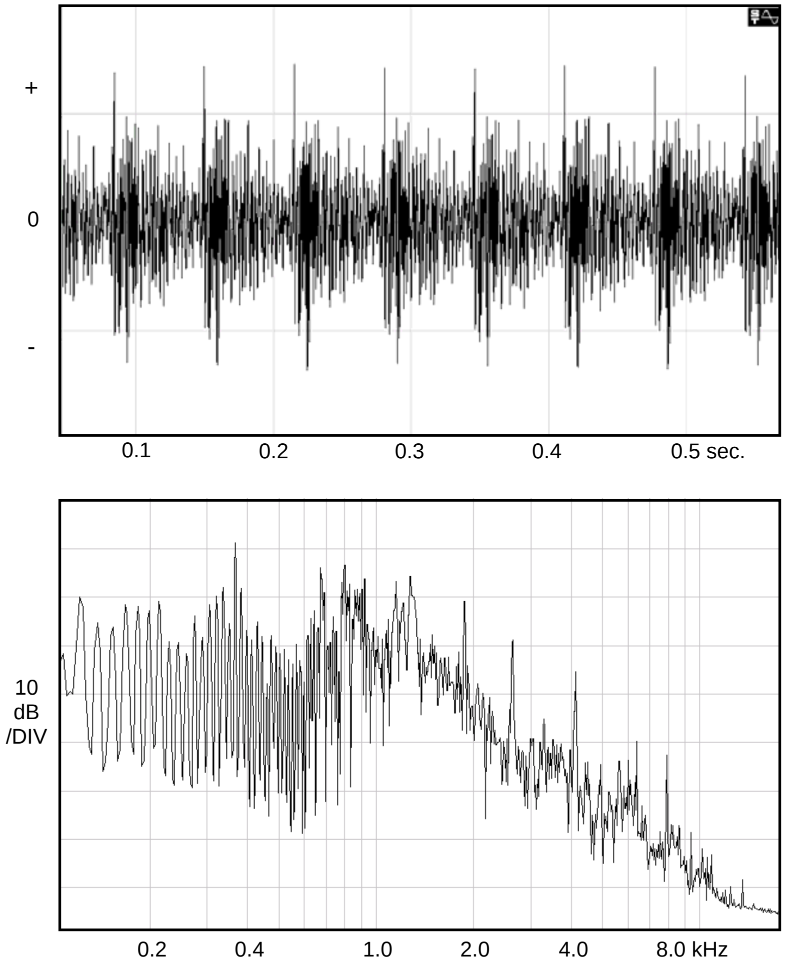

Figure 1

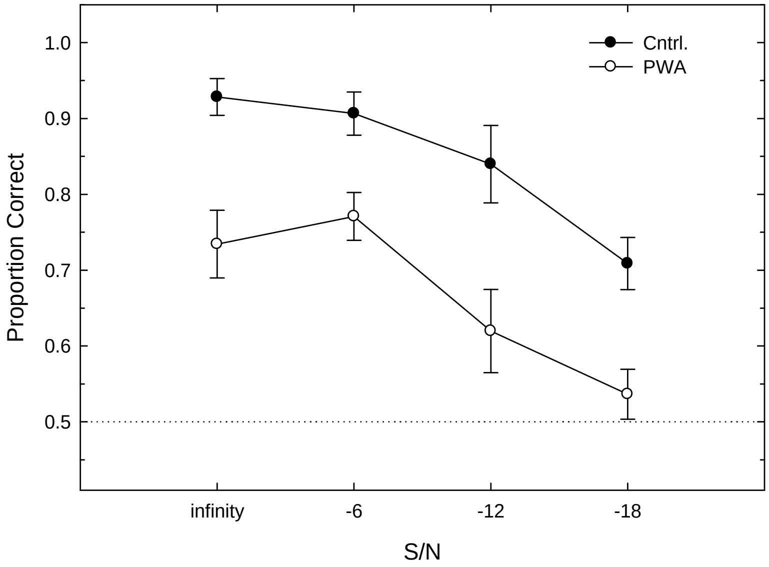
Proportion Correct
1.0
0.9
0.8
0.7
0.6
0.5
Cntrl.
PWA
infinity
-6
-12
-18
S/N

Figure 2

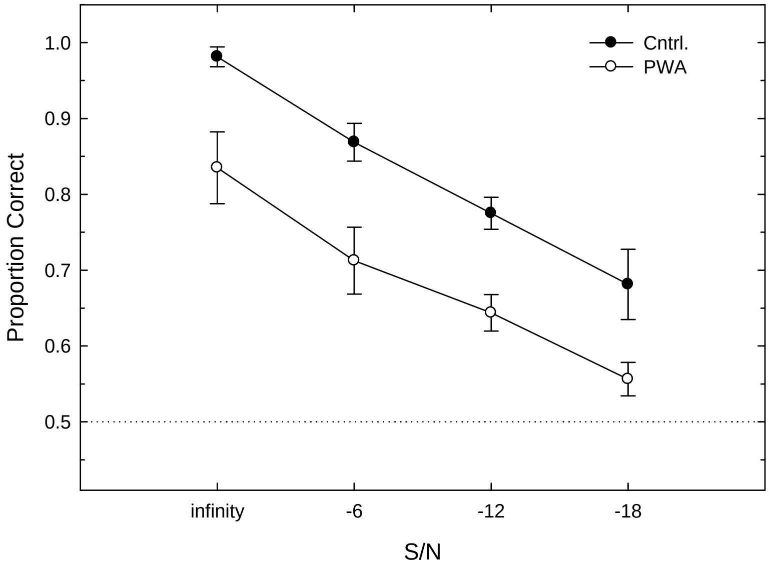
1.0
0.9
0.8
0.7
0.6
0.5
Proportion Correct
● Cntrl.
○ PWA
infinity
-6
-12
-18
S/N

Figure 3

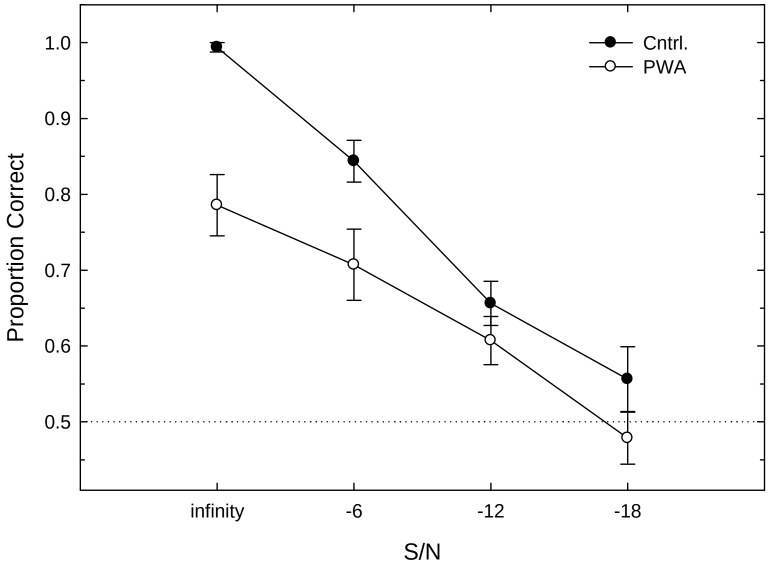
Proportion Correct
1.0
0.9
0.8
0.7
0.6
0.5
infinity
-6
-12
-18
S/N
● Cntrl.
○ PWA

Figure 4

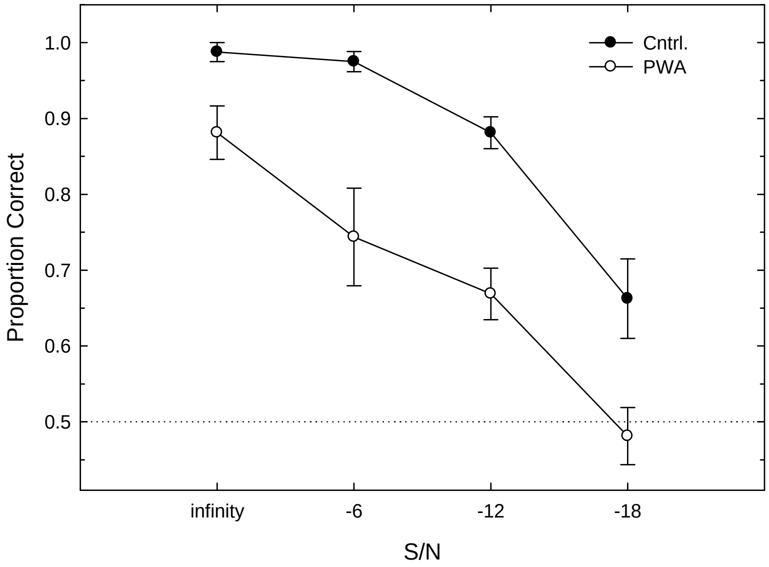
Proportion Correct
1.0
0.9
0.8
0.7
0.6
0.5
● Cntrl.
○ PWA
infinity
-6
-12
-18
S/N

Figure 5