Speech Perception in MRI Scanner Noise by Persons With Aphasia

Eric W. Healy
Dana C. Moser
K. Leigh Morrow-Odom
University of South Carolina, Columbia

Deborah A. Hall
MRC Institute of Hearing Research, Nottingham, United Kingdom

Julius Fridriksson
University of South Carolina

Purpose: To examine reductions in performance on auditory tasks by aphasic and neurologically intact individuals as a result of concomitant magnetic resonance imaging (MRI) scanner noise.

Method: 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 3 Tesla MRI scanner at 3 signal-to-noise (S/N) ratios.

Results: Across the 4 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 2 listener groups in any task.

Conclusions: Depending on 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, functional MRI data from aphasic and control individuals may be interpreted without complications associated with large interactions between scanner noise and performance reduction.

KEY WORDS: speech perception, aphasia, magnetic resonance imaging, noise

Functional magnetic resonance imaging (fMRI) is a technique that is increasingly being applied in the study of brain–behavior relations. 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 for which 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. The noise associated with MRI can reach 130- to 140-dB sound pressure level (SPL) at 3 Tesla (T), the magnet strength at which human fMRI experiments are increasingly being conducted (Foster, Hall, Summerfield, Palmer, & Bowtell, 2000; Ravicz, Melcher, & Kiang, 2000). Much of the work examining the influence of acoustic scanner noise has been directed toward its capacity to interfere with the study of hearing or language by producing activation of various brain regions (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 in the study of brain function in persons with aphasia (PWA). Indeed, the use of fMRI in the study of processing defects in aphasia has increased dramatically in recent years (cf. Price & Crinion, 2005). Sparse fMRI design (Fridriksson & Morrow, 2005; Hall et al., 1999), in which stimuli are presented during brief periods of relative quiet, is one method that has been used to reduce the influence of concomitant scanner noise (e.g., Fridriksson & Morrow, 2005; Fridriksson, Morrow, Moser, & Baylis, 2006; Fridriksson, Morrow, Moser, Fridriksson, & Baylis, 2006; Martin et al., 2005). However, this technique requires sessions that are longer than those of traditional continuous scanning to acquire the same amount of imaging data, and PWA can be intolerant of long sessions.

A number of studies have reported that decreases in task performance in the presence of competing auditory stimuli are larger for PWA than for individuals employed as controls. 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 fewer utterances were produced under divided attention relative to isolation and that this reduction was greater for PWA. Murray (2000) also found decreased word retrieval and pure-tone discrimination by aphasic persons compared with normal controls on both focused and divided attention tasks using pure-tone competing stimuli. Indeed, it has been suggested that the language-processing deficits in PWA are strongly associated with 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 control participants (i.e., persons who do not have aphasia). This performance was examined in four tasks spanning a large portion of the linguistic continuum. Across these tasks, performance was assessed in silence and, because determination of the signal-to-noise (S/N) ratio corresponding to particular scanning sessions can be difficult, in the presence of scanner noise at a range of S/N values.

Method

Participants

Sixteen native English-speaking listeners participated. One group consisted of 8 PWA who were recruited from the University of South Carolina Speech and 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. Of the 8 participants, 5 were women and 3 were men, and all were right-handed. The mean level of education for this group was 15 years (ranging from 11 to 22 years). A group of 8 control participants also served. These individuals were matched for age within 2 years

Table 1. Characteristics of the aphasic participants.

Characteristic	PWA 1	PWA 2[a]	PWA 3	PWA 4	PWA 5	PWA 6	PWA 7	PWA 8
Age	65	61	70	58	49	46	41	68
Gender	F	M	F	M	M	F	F	F
Education (in years)	12	22	17	12	11	16	18	12
Post onset (in years)	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	86.0	43.4	61.6
RTT	13.20		9.75	11.44	12.36	12.80	11.46	12.06

Note. PWA = persons with aphasia; WAB—AQ = Western Aphasia Battery–Aphasia Quotient; RTT = Revised Token Test; M = male; F = female.

[a]This individual was unavailable to complete the RTT.

of their counterpart with aphasia. All participants had pure-tone audiometric thresholds of 20 dB hearing level (HL) or better at octave frequencies ranging from 250 to 4000 Hz (American National Standards Institute, 1996). The exception was 1 PWA, who had a threshold of 30 dB HL at 4000 Hz in one ear.

Stimuli

Task 1: Complex-tone frequency discrimination

In the first task, listeners judged whether a pair of complex tones had the same or different pitch. Stimuli 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 3, 6, or 9 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 2. Furthermore, the spectrum of each tone burst was shaped using a digital one-third octave filter bank (composed of thirty 1,000-order finite impulse response bandpass filters) to match the long-term average amplitude spectrum of the speech items in Task 2.

Task 2: Minimal-pair syllable discrimination

In this task, listeners judged whether two monosyllabic nonsense words were the same (e.g., kɛp/kɛp) or different (e.g., təp/dəp). 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 4 pairs served as practice stimuli. Lists of the speech stimuli used are presented in the Appendix.

Task 3: Lexical decision

In this task, listeners determined if auditory presentations were real words (e.g., attitude) or nonsense words (e.g., andiance). Forty words and 40 nonwords 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 nonwords. The stimuli were divided into four lists of 10 words and 10 nonwords each, and the lists were approximately balanced for number of syllables and phonological complexity. An additional 4 words and 4 nonwords served as practice stimuli.

Task 4: Sentence plausibility

In this task, listeners judged whether short sentences were plausible (e.g., "Bread goes stale") or implausible (e.g., "Cows read books"). Simple three-word sentences were created using concrete, frequently occurring words. Forty plausible and 40 implausible sentences were created. Half of the sentences were in the subject–verb–direct object form, and the other half were in the subject–verb–adjective form. They were divided into four lists of 10 plausible and 10 implausible sentences each and were balanced for direct object versus adjective construction, and were approximately balanced for the number of syllables and phonetic content. An additional two plausible and two implausible sentences served as practice stimuli.

Scanner noise recording

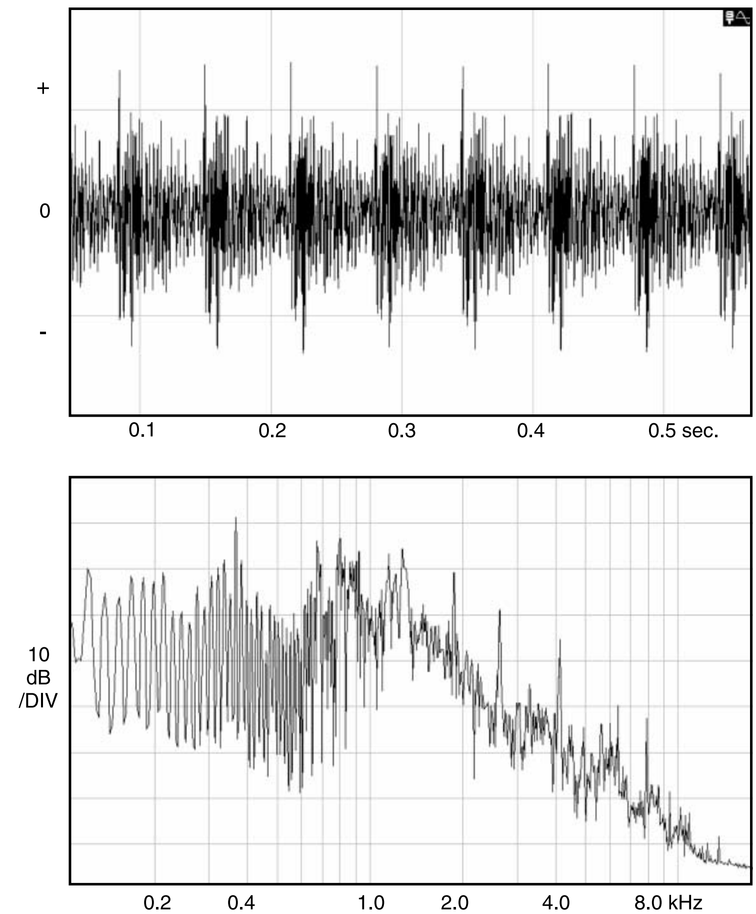
A recording from within the bore of a 3T Philips Intera fMRI scanner was used as the noise signal. The procedures used to record the scanner noise followed those of Foster et al. (2000). The interested reader is directed there for details on this procedure and the substantial safety issues involved when recording in the presence of the strong magnetic field. Briefly, the recording was made by fixing a nonferrous microphone (Brüel&Kjær 4165) connected to a shielded and nonferrous 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 are displayed in Figure 1. An echo planar sequence was used with the following specifics: repetition time (TR) = 2 s, echo time (TE) = 44 ms, matrix = 64 × 64, voxel size = 3.25 × 3.25 × 5 mm, sensitivity encoding (SENSE) = 2. The noise had a root mean square (RMS; or average over time) level that measured 95 dBA with an instantaneous peak level of 107 dBA.

Stimulus preparation

The speech items for Tasks 2–4 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

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



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 tone burst and speech item, as well as the scanner noise, was equated in level. This was done by scaling the digital files so that the RMS levels of the steady-state tones and scanner noise, and the peaks of the slow-response RMS averages of the speech, were within 0.5 dB of one another when transduced by headphones (Sennheiser HD 250 II) and measured on a flat-plate headphone coupler (Larson Davis AE 101) using a Type 1 sound level meter (Larson Davis 800B). To create the signal-in-noise stimuli for each of the tasks, the signals were attenuated by the appropriate amount and digitally mixed with the scaled scanner noise to yield S/N ratios of −6, −12, and −18 dB. These values were selected to produce a range of performance values and to represent the wide range of S/N values used across various scanning settings. An additional condition in which scanner noise was absent (S/N infinity) was also prepared. Headphone presentation of mixed sound files (rather than presentation of stimuli during scanning) was employed to allow better control over the S/N present at the level of the inner ear. To avoid the increased masking that occurs when a signal occurs coincident with the onset of a masker (Bacon & Healy, 2000; Zwicker, 1965), the scanner noise (or silence in the S/N infinity condition) began 1.5 s prior to the onset of each signal or signal pair and extended 0.75 s 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 7 normal-hearing (same 20 dB HL criteria) adults aged 22–26 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 used in the formal experiment. It was found that the mean percentage correct for each of the four stimulus subsets was within 5% of the grand mean for all the subsets making up Tasks 2 and 4. However, for

Task 3, 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 percentage 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 were also used to collect responses (E-Prime v1.0, Psychology Software Tools). The files were converted to analog form (Edirol UA25) and presented diotically over the Sennheiser headphones. The level of the scanner noise was set to 70 dBA at each ear. The four auditory tasks, and the four noise conditions within each task, were heard in a different random order for each participant. In addition, the correspondence between subset list and noise condition was randomized for each participant. However, this randomization was identical for a given PWA and their corresponding control participant. The listeners heard all of the conditions 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 in each noise condition, and the same-frequency pair was presented 12 times in each condition 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 was 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 condition.

Listeners responded by pressing a large (63 mm diameter) unlabeled green or red button after each trial (green for responses "same," "word," or "plausible" and red for "different," "nonword," or "implausible"). The subsequent trial began 2 s 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 together within a 9 ft × 10 ft double-walled audiometric booth (IAC 103024) and required a single 1-hr session.

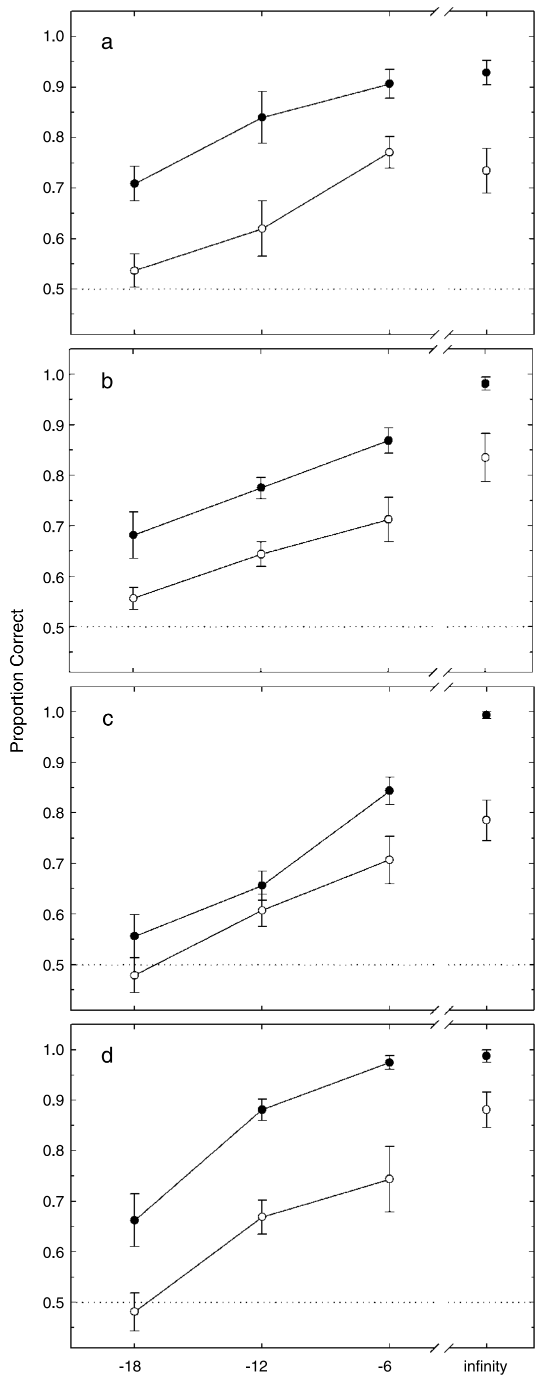
The PWA also underwent neuropsychological testing during a separate session to assess overall language and auditory comprehension. This test battery was administered by a speech-language pathologist and included the Western Aphasia Battery (WAB; Kertez, 1982) and the Revised Token Test (RTT; McNeil & Prescott, 1978). Testing occurred 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 to define the aphasia type and severity. The WAB provides an aphasia quotient, which is an overall language score derived from the following subtests: Spontaneous Speech, Comprehension, Naming, and Repetition. The RTT was administered to assess auditory comprehension. The test 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. As can be seen, these individuals displayed a range of aphasia types and severities. Performance on the complex-tone frequency discrimination task (Task 1) is displayed in Figure 2a. As the figure shows, although considerable variability was observed, this variability was generally similar for both participant groups. Not surprisingly, performance of the PWA was poorer than that of their normal counterparts in all conditions, despite the fact that both groups of participants 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 × 4 Noise Conditions) analysis of variance (ANOVA) with one repeated factor indicated that the main effects of listener group and noise condition were significant at $p < .001$. 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 2b. 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 ANOVA indicated that the main effects were significant at $p < .001$, but that the interaction was not significant, $F(3, 42) = 0.1$ $p = .95$. Performance on the lexical-decision task (Task 3) is displayed in Figure 2c. One of the PWA was unable to complete this task, so data are shown for the remaining 7 participants. Again, a two-way ANOVA indicated that the main effects were significant at $p < .001$, but that the interaction was not, $F(3, 39) = 2.3$ $p = .09$. Finally, performance on the sentence plausibility task (Task 4) is displayed in Figure 2d. As in all other tasks, performance was poorer for the PWA, and both groups fall as a

Figure 2. Group mean accuracy and standard errors for participants with aphasia (open symbols) and for normal controls (filled symbols). The tasks involved (a) discrimination of complex tone pairs having same or different frequencies, (b) same–different judgments of minimal-pair nonsense syllables, (c) lexical decision of words and nonwords, and (d) plausibility of short sentences. The signals were presented in silence (signal-to-noise [S/N] infinity) or in a background of magnetic resonance imaging scanner noise at the relative levels indicated. Chance performance is indicated in each panel by the dotted line.



function of S/N. In accord with the previous analyses, a two-way ANOVA indicated that the main effects were significant at $p < .001$, but that the interaction was not, $F(3, 42) = 1.1$, $p = .38$.

Discussion

The deleterious impact of noise on the reception of speech by listeners having normal hearing has been well studied (for review, see Assmann & Summerfield, 2004). Although performance can be influenced by a variety of factors including noise and speech type, the changes in sentence plausibility recognition observed here are in general accord with classic literature involving auditory intelligibility changes as a function of S/N (Sumby & Pollack, 1954). A considerable amount is also known about the limitations to speech perception in noise imposed by conditions such as cochlear hearing impairment (cf. Moore, 1998). In sharp contrast, little is known about the influence of cognitive impairments such as aphasia 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, given the observation that PWA exhibit poor auditory comprehension in the presence of auditory distraction, that they 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. Because the talker, scanner noise recording, and procedures were the same, results across the various tasks may be directly compared. As Figure 2 shows, 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 exceptionally poor performance displayed by aphasic individuals on auditory tasks in noise may simply be a function of poorer baseline performance in quiet. Lower baseline performance results in a restriction of the performance range from baseline level of proficiency down to chance. Because performance was found to decrease for all participants as a function of noise, PWA may simply reach the performance floor before (at more favorable S/Ns than) other individuals.

Noise associated with MRI can be dealt with in a number of ways. It can be reduced by restricting the mobility of the gradient coil or by isolating vibration transmission. Software modifications to existing installations are also possible. Slower ramp times ("smooth gradients") can reduce noise, but may compromise the quality of magnetic resonance (MR) images. Active noise cancellation systems have been developed that deliver the ambient noise signal to the ear canal following phase inversion (Chambers, Akeroyd, Summerfield, & Palmer, 2001). However, the true benefits are limited by the scanner vibrations conducted through the body because cancellation only eliminates air-conducted sound energy in the ear canal.

Another method to limit the disruptive influence of scanner noise involves sparse imaging. The strength of the sparse design comes from the silent periods between volume collections. For example, a noise-filled volume acquisition time (TA) of 3 s and a time between the start of each volume acquisition (TR) of 10 s yield a silent interval between TAs of 7 s. This interval is sufficient for both presentation of stimuli and collection of responses. However, a continuous fMRI sequence with a corresponding 3-s TR will acquire 200 full brain volumes in 10 min, whereas the sparse fMRI sequence will acquire only 60 volumes in the same amount of time. Thus, although sparse scanning techniques offer substantial advantages, it is clear that continuous scanning is desirable in some situations. The interested reader is directed to reviews by Amaro et al. (2002) and by Moelker and Pattynama (2003) for comprehensive descriptions of the sources of acoustic noise in MR imaging and descriptions of experimental paradigms used to limit the influence of this noise.

Current efforts toward reducing the influence of scanner noise are largely directed toward attenuating the level of the noise at the participants' ear. Detailed measurements of EAR foam earplugs have indicated attenuation of 25–29 dB in the frequency range where most of the gradient noise resides (Ravicz & Melcher, 2001). In fMRI studies using acoustic stimuli, earmuffs are often employed. However, neither of these devices can protect against bone-conducted noise, and they provide no more than 40 dB of attenuation even when used in combination (Ravicz et al., 2000).

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, which can have the effect of reducing effective S/N (cf. Moore, 1998). It should be noted that many of the potential participants considered for the current study had moderate-to-severe hearing losses, which made them ineligible for participation. Although the current results are free of this confound and may be attributed directly to neurological state, this additional complication associated with hearing losses greater than approximately 30 dB HL must be considered when testing older individuals on auditory tasks in background noise.

Conclusion

The exact specification of S/N in fMRI studies using auditory stimuli is a potentially 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. Furthermore, 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 with 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. However, it is important that potential differences in cochlear hearing loss across groups be considered.

Acknowledgments

This work was supported in part by National Institute on Deafness and Other Communication Disorders Grants DC05795 and DC05915. The valuable assistance of Julia Lumb and Holly Smithson is gratefully acknowledged, as are comments on a version of the article from Barbara Cone-Wesson, Richard Wilson, Anthony Salvatore, and an anonymous reviewer.

References

Amaro, E., Jr., Williams, S. C. R., Shergill, S. S., Fu, C. H. Y., MacSweeney, M., Picchioni, M. M., et al. (2002). Acoustic noise and functional magnetic resonance imaging: Current strategies and future prospects. *Journal of Magnetic Resonance Imaging, 16,* 497–510.

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

Assmann, P., & Summerfield, Q. (2004). Perception of speech under adverse conditions. In S. Greenberg, W. A. Ainsworth, A. N. Popper, & R. R. Fay (Eds.), *Speech processing in the auditory system* (pp. 231–308). New York: Springer.

Bacon, S. P., & Healy, E. W. (2000). Effects of ipsilateral and contralateral precursors on the temporal effect in simultaneous masking with pure tones. *The 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.

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. *The 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., & Baylis, G. (2006). Age related variability in cortical activity during language processing. *Journal of Speech, Language, and Hearing Research, 49,* 690–697.

Fridriksson, J., Morrow, K. L., Moser, D., Fridriksson, A., & Baylis, G. (2006). Neural correlates of anomia recovery in aphasia. *NeuroImage, 32,* 1403–1412.

Hall, D. A., Haggard, M. P., Akeroyd, M. A., Palmer, A. R., Summerfield, A. Q., Elliott, M. R., et al. (1999). "Sparse" temporal sampling in auditory *f*MRI. *Human Brain Mapping, 7,* 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, England: Psychology Press.

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

Martin, P. I., Naeser, M. A., Doron, K. W., Bogdan, A., Baker, E. H., Kurland, J., et al. (2005). Overt naming in aphasia studied with a functional MRI hemodynamic delay design. *Neuroimage, 28,* 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.

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.

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, L. L., Holland, A. L., & Beeson, P. M. (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.

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. (2001). Isolating the auditory system from acoustic noise during functional magnetic resonance imaging: Examination of noise conduction through the ear canal, head, and body. *The Journal of the Acoustical Society of America, 109,* 216–231.

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

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

Sumby, W. H., & Pollack, I. (1954). Visual contributions to speech intelligibility in noise. *The Journal of the Acoustical Society of America, 26,* 212–215.

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

Received April 28, 2006

Accepted August 26, 2006

DOI: 10.1044/1092-4388(2007/023)

Contact author: Eric W. Healy, Department of Communication Sciences and Disorders, University of South Carolina, Columbia, SC 29208. E-mail: ewh@sc.edu.

Appendix (p. 1 of 4). Speech materials employed for Tasks 2–4.

Task 2: Minimal-Pair Syllable Discrimination
Examples: sɛn / sɛn, dət / dət, bɛp / dɛp, mɪb / mɪm

Subset 1

Different	Same
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	kaib / kaib
nəf / fəf	nəd / nəd

Subset 2

Different	Same
kib / tib	təp / təp
pɛb / pɛm	baun / baun
bɪp / mɪp	pɛf / pɛf
taif / taiv	faib / faib
sət / səp	saud / saud
faib / faim	nək / nək
naup / laup	nɪs / nɪs
laib / laip	faig / faig
heip / heib	vəl / vəl
nap / naf	puk / puk

Subset 3

Different	Same
kaut / kaus	sɛf / sɛf
fɪk / fɪp	veid / veid
baip / daip	daib / daib
təs / dəs	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

Appendix (p. 2 of 4). Speech materials employed for Tasks 2–4.

Subset 4

Different	Same
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

Subset 1

Nonwords	Words
andiance	attitude
pitaro	character
drister	miracle
foaster	concept
hetal	effort
vallige	manner
sprool	bonus
plen	thought
afe	clue
fide	fact

Subset 2

Nonwords	Words
baranter	idea
halocle	gravity
sogmy	episode
mither	moment
cottee	tribute
stadent	theory
sping	woe
drim	plea
pib	purpose
weast	length

Appendix (p. 3 of 4). Speech materials employed for Tasks 2–4.

Subset 3

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

Subset 4

Nonwords	Words
tanacco	analogy
biffle	opinion
trabite	principle
mirtage	crisis
sammer	folly
slurch	valour
pline	thing
clee	pact
dend	wrath
lutter	treason

Task 4: Sentence Plausibility
Examples: Eggs drink coffee. Leaves change color. Fire is cold. Cherries are red.

Subset 1

Implausible	Plausible
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.

Appendix (p. 4 of 4). Speech materials employed for Tasks 2–4.

Subset 2

Implausible	Plausible
Guns send letters.	Cars use gas.
Fleas jump rope.	People walk dogs.
Tables eat snow.	Pastors give sermons.
Doors keep secrets.	Maps give directions.
Birds boil potatoes.	Kids grow older.
Balls are square.	Rocks are hard.
Pumpkins are blue.	Fire is hot.
Glass is fluffy.	Cheetahs are fast.
Sandpaper is smooth.	Water is clear.
Rainbows are colorless.	Gum is sticky.

Subset 3

Implausible	Plausible
Phones leak oil.	People eat food.
Chickens make bricks.	Dentists fix teeth.
Pictures write songs.	Squirrels climb trees.
Nuns wear tutus.	Cups hold liquid.
Cabinets grow hair.	Hammers pound nails.
Ice is warm.	Rings are round.
Sprinters are slow.	Apples are red.
Fruit is greasy.	Water is wet.
Gasoline is tasty.	Chips are salty.
Ants are enormous.	Sheep are wooly.

Subset 4

Implausible	Plausible
Ears taste food.	Cows make milk.
Pets wave flags.	Cats chase mice.
Carpets ask questions.	Watches keep time.
Tires play Bingo.	Children eat cookies.
Books use electricity.	Factories make cars.
Rain is dry.	Juice is liquid.
Pens are sour.	Slugs are slimy.
Air is muddy.	Grass is green.
Skyscrapers are tiny.	Thunder is loud.
Cheeseburgers are tasteless.	Pillows are soft.