Assessing the Influence of Scanner Background Noise on Auditory Processing. II. An fMRI Study Comparing Auditory Processing in the Absence and Presence of Recorded Scanner Noise Using a Sparse Design

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Abstract: Several studies reported decreased signal intensities within auditory areas for experimental designs employing continuous scanner background noise (SBN) in comparison to designs with less or no SBN. This study examined the source for this SBN-induced masking effect of the blood oxygenation level-dependent (BOLD) response by directly comparing two experimental sessions with the same auditory stimulation, which was presented either with or without recorded scanner background noise (RecSBN). Ten subjects listened to a series of four one-syllable words and had to decide whether two of the words were identical. The words were either presented with a silent background or with added RecSBN. This was then contrasted with either silence or RecSBN. A sparse temporal sampling method was used in both sessions, which enabled us to directly assess the influence of RecSBN without varying scanning parameters, acquisition quantities, or auditory stimulations. Our results suggest that previously reported SBN-induced masking of the BOLD response in experimental designs with SBN might be caused by an interaction between increased baseline levels and nonlinearity effects within auditory cortices. Adding SBN to an experimental condition does not enhance signal intensities to the same degree that SBN does when presented with a silent background, and therefore contrasting an experimental and baseline condition that both have SBN may lead to signal decreases. In addition, our study shows this effect is greatest in Heschl's gyrus, but can also be observed in higher-order auditory areas. *Hum Brain Mapp 28:721–732, 2007.* © 2006 Wiley-Liss, Inc.

Key words: fMRI; auditory cortex; scanner background noise; sparse temporal sampling

INTRODUCTION

Increasingly, research studies have addressed the issue of scanner background noise (SBN) in functional MRI (fMRI), which can lead to a series of problems such as masking the response within auditory regions or making it difficult to perceive the presented auditory stimuli. This noise, which accompanies every conventional fMRI measurement can be very loud [e.g., Counter et al., 2000; Moelker and Pattynama, 2003; Price et al., 2001], and is caused by the vibration of the gradient coil resulting from

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Lorentz forces generated by the current in the coil. Several studies examined the influence of SBN on stimulus delivery as well as signal intensity within auditory regions [e.g., di Salle et al., 2001; Gaab et al., 2006; Hall et al., 1999; Shah et al., 1999, 2000; for reviews, see Amaro et al., 2002; Moelker and Pattynama, 2003], as well as nonauditory areas [e.g., Cho et al., 1998; Elliott et al., 1999; Zhang et al., 2005], and found increased auditory responses in designs with a lesser degree of SBN.

Several studies examined the influence of recorded SBN (RecSBN) on primary and secondary auditory cortex using fMRI designs that employ less or no SBN during auditory stimulation or other "silent methods" such as EEG and MEG that silently measure brain correlates. One of these studies revealed a typical hemodynamic response function with a peak about 4–5 s after stimulus onset [Hall et al., 2000]. Others showed an influence of both amplitude and duration change of the recorded SBN on auditory areas [Matthiak et al., 2002]. Simultaneous presentation of RecSBN and auditory stimuli also leads to a decrease in amplitude and an increase in ERP latency for pure tones, musical chords, and more complex tasks such as auditory working memory [Novitski et al., 2001, 2003]. Additionally, RecSBN seems to affect linguistic processing to a different degree than early stages of auditory processing. Herrmann et al. [2000] reported SBN-induced suppression of MEG responses to sentences within a time window of 120–200 ms, which reflects linguistic processing. No suppression was found earlier that would reflect nonlinguistic, auditory processing on the perceptual level.

It was previously proposed that the signal decrease in auditory areas is a result of SBN-induced raised baseline levels in control conditions [Edmister et al., 1999; Talavage et al., 1999], which leads to activation decreases when contrasting experimental and control conditions in an fMRI experiment with continuous SBN. Talavage and Edmister [2004] examined whether the nonlinear addition of the hemodynamic response function (HRF) might be the leading cause for the decrease when comparing experimental design with varying degrees of SBN. By varying the degree of SBN, they directly examined the possible interaction between stimulus presence and degree of SBN, although signal intensities in response to auditory stimulation in isolation (no SBN) were not obtained and stimuli were presented in 24-s blocks with continuous auditory stimulation. The authors ascribed nonlinearity of the fMRI response within auditory regions to spectral overlap of the stimuli. Furthermore, they suggested that the decrease of auditory activation in the presence of SBN results from a combination of the observed nonlinearity and an increase of the mean baseline level in the control conditions.

Nevertheless, it remains unclear whether the proposed nonlinearity varies by cortical area or might be different for an active higher-order auditory task. Furthermore it is uncertain whether these nonlinearity effects can also be observed for event-related auditory designs with silent intervals between short stimuli, which is often used with a sparse temporal sampling scanning approach. Previous studies examining the influence of the degree of SBN on auditory areas by varying the experimental scanning design were unable to directly compare the cortical response to a stimulus perceived with and without SBN within the same scanning design.

In Part I of this study [Gaab et al., 2006], we compared acquisitions with and without SBN in an event-related (ER) sparse sampling task and demonstrated significant activation reductions in auditory areas in the acquisition with SBN. However, that study utilized a continuous acquisition from which selected ER samples were extracted for analysis of the SBN case. Therefore, we felt that an additional comparison would be important, in which the acquisition was unchanged except to add SBN during the stimulus and control presentation periods alone, in order to further examine dynamics of the baseline modulation with SBN. This was not possible in part I due to the continuous scanner noise [Gaab et al., 2006].

The aim of this study was to investigate the influence of recorded SBN on signal intensities within primary and higher-order auditory regions using an active verbal auditory task with increased cognitive demand in relation to previous studies assessing the influence of SBN on signal intensities. We applied a sparse temporal sampling design [e.g., Belin et al., 1999; Gaab et al., 2003, 2006; Hall et al., 1999] with varying delays between auditory stimulation and image acquisition and compared two experimental designs that had exactly the same auditory stimulation that was presented with or without RecSBN. In addition, this was contrasted with either a silent baseline (no contamination with SBN) or a baseline with SBN that enabled direct examination of the stimulus-SBN interaction within auditory areas.

SUBJECTS AND METHODS

Participants

Ten normal right-handed volunteers (age range: 18–22, mean age: 19; five males and five females) were recruited. Subjects had no history of neurological or hearing impairment. Informed consent to take part in a study approved by the Stanford University panel on Human Subjects in Medical Research was obtained from each subject.

Auditory Setup Procedure

Stimuli were delivered using pneumatic headphones which provide ear protection (Avotec, Stuart, FL). Tasks were programmed using Eprime (Psychology Software Tools, PST, Pittsburgh, PA) running on a PC with SoundBlaster audio card (Creative Technology, Singapore). Stimuli were sampled and presented at 44 kHz. Subjects underwent a three-step volume setup procedure prior to scanning but after placement in the magnet. During the first step subjects listened to randomly chosen words and were

asked to increase or decrease the amplitude of the words using button pushes until they reached their own comfortable amplitude with no SBN. These amplitude values were used during the experimental stimulation when words were presented with a silent background. During the second step, subjects listened to randomly chosen words that were presented with recorded scanner noise. The MRI scanner was running during this step but interleaved with the auditory stimuli (clustered volume acquisition; repetition time, TR, = 6 s). Subjects were first asked to adjust the volume of the recorded SBN (RecSBN) to the "real" SBN (RealSBN), which occurred every 6 s for 2 s. Later during the experiment, this value was used during the presentation of RecSBN without words.

Subjects were then asked to adjust the volume of the words so that they were able to hear them clearly with the RecSBN in the background. The values so obtained were entered in the third step of the auditory setup procedure. Here, subjects heard 2 s of RealSBN followed by three recorded words with RecSBN in the background. This was repeated four times with slight variations of the volume of both words and RecSBN. Subjects were asked to choose their personally preferred combination. These values were used during the experimental stimulation when RecSBN was presented. In this fashion, three amplitudes were obtained for 1) words with a silent background; 2) RecSBN (perceived equal in amplitude to that of the actual scanner noise); and 3) words together with RecSBN.

Stimuli and Experimental Tasks

All subjects underwent two experimental runs for which the order of the runs was counterbalanced across subjects. During one of the two runs subjects listened to 48 series of four recorded one-syllable words (overall duration = 4 s) and had to decide by pressing one of two buttons whether two of the four presented words were the same or not Fig. 1.1A). This experimental condition was contrasted with a silent condition (16 sets of no-stimulus for 4 s, Fig. 1.1B) [see also Gaab et al., 2006]. The other run (scanner noise task) had the same timing and auditory stimulation as the previous one, but was modified by playing 4 s of RecSBN together with the words (Fig. 1.2A). In this case the experimental condition was contrasted with a noise condition (4 s of recorded scanner noise, Fig. 1.2B). This enabled us to directly compare the influence of background scanner noise on auditory processing without varying the scanning procedure, a confound present in some of the prior studies.

Overall, 47 concrete one-syllable words spoken by a female voice were presented in four-word sequences. The recorded words had an average concreteness factor of 463 (range: 234–614) and an average frequency factor of 56 (range: 1–362) based on the MRC Psycholinguistics Database (Machine Usable Dictionary, v. 2.0). All words were recorded using Audacity (http://audacity.sourceforge.net/) and were normalized for their root-mean-square energy

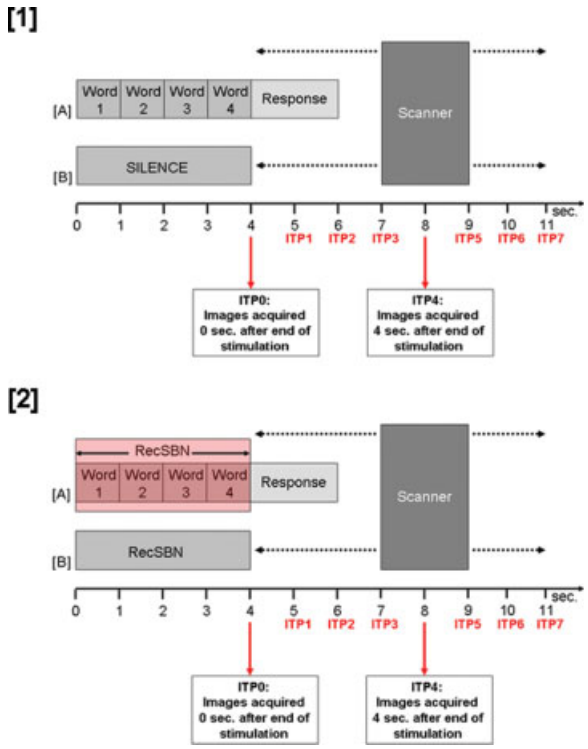

Figure 1.

1) Experimental stimulation for the design without RecSBN. **A:** Experimental condition (only words). **B:** Control condition (silence) as well as image acquisition for STsamp. The delay between the end of the auditory stimulation and the beginning of the image acquisition was varied over 8 s. Each ITP corresponds to the volume acquired after the end of auditory stimulation, e.g., ITP0 corresponds to volumes acquired 0 s after the end of the auditory stimulation, and ITP5 corresponds to volumes acquired 5 s after the end of the auditory stimulation. 2) Experimental stimulation for the design with implemented RecSBN. **A:** Experimental condition (words presented simultaneous with RecSBN). **B:** Control condition (only RecSBN) as well as image acquisition for STsamp. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

content. The number of four-word sequences (n = 48) did not differ between the two conditions. Magnitude spectra were obtained separately for all words using a Hanning-windowed Fourier Transform. An overall magnitude spectrum for the words was calculated by averaging over all of the word spectra (Fig. 2). The scanner noise was recorded using a nonmagnetic (electrostatic) microphone with spectral response extending from 50 Hz to 8 kHz, placed in the magnet on the RF coil close to where the left ear would be. The RecSBN has most of its spectral density at 1 kHz or above, while the words have most of their energy at less than 1 kHz. The functional imaging sequence was started in continuous scan mode while a 4-s record was made using SoundEdit 16 software (Macromedia, San Francisco, CA) on a Macintosh computer. The magnitude

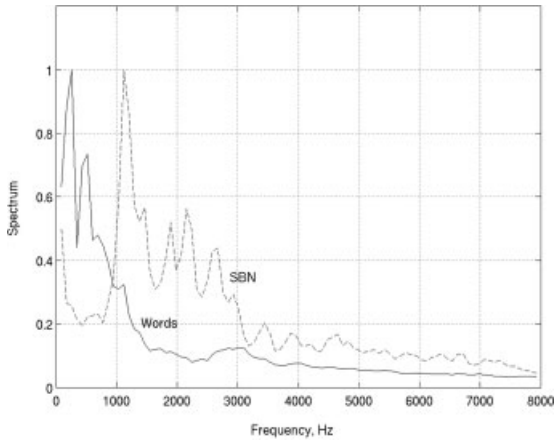

Figure 2.
Comparison of the amplitude spectrum for recorded scanner noise (SBN) and the average of the spectra for the 47 words. Amplitudes were normalized to the same value of the highest peak for clarity.

spectrum for the SBN was obtained using a Hanning-windowed Fourier Transform (Fig. 2). The auditory setup and the fMRI tasks were programmed in Eprime (http://www.pstnet.com). Despite potential limitations in the dynamic range of the recording and playback instruments, subjects reported that the RecSBN was a faithful replica of the real SBN.

Imaging Procedure

The fMRI scanning was conducted with a 3.0T GE Signa scanner (General Electric, Milwaukee, WI) using a custom-built volume headcoil. Head motion was controlled by clamps mounted on the coil to stabilize the headphones. Sagittal T1 localizer scans were collected as well as a T1-weighted whole-brain anatomy scan (256 × 256 voxels, 0.86 mm in-plane resolution, 1.2 mm slice thickness) for the purposes of normalization of functional data into common stereotactic space. High-order shimming was employed with a subject-specific ROI and the scanner's built-in software [Kim et al., 2002]. The fMRI data were collected using a spiral in/out T2* pulse sequence [Glover and Law, 2001] with 30 slices covering the entire brain (64 × 64 voxels, 3.43 mm in-plane resolution, TE 30 ms, 4 mm slice thickness with 0.5 mm slice skip). Although the TR was kept constant at 16 s (flip angle 90°), the start of the 2-s clustered MR acquisition (30 slices in 1.995 s) varied with regard to the onset of auditory stimulation by pseudorandomly jittering the start of the auditory stimulation frame (e.g., 4 s of words or 4 sec of silence) within the 16-s TR period in 1-s steps (Fig. 1.2A). This jittering process [for details, see Belin et al., 1999; Gaab et al., 2003] resulted in eight image time points (ITPs). Each ITP corresponds to the volume acquired after the end of auditory stimulation, e.g., ITP0 corresponds to volumes acquired 0 s after the end of the auditory stimulation, and ITP5 corresponds to volumes acquired 5 s after the end of the auditory stimulation, and therefore each ITP samples a different fraction of the HRF. Overall, 66 time frames were acquired over the entire duration of 17 min and 34 s. Both the control and experimental conditions occurred during periods of scanner inactivity. The previously determined scanner volume settings were used for stimulus presentation.

In a lengthy ER scan protocol such as that employed here, it is important to establish accurate timing between the scanner and the stimulus presentation computer. In our case the scanner was triggered once by the start of the Eprime stimulus program. Because care was taken in writing both the spiral fMRI sequence and the Eprime code, timing errors between the pulse sequence and the Eprime program were measured to be only several ms at the end of the scan.

fMRI Data Analysis

fMRI data preprocessing

After image reconstruction, both sets of axial images were slice time-corrected. Then all 132 images were realigned to the first image of the first run and coregistered with the corresponding T1-weighted high-resolution dataset. Spatial normalization was done in three steps. First, the skull of the T1-weighted high-resolution dataset was stripped using FSL (see http://www.fmrib.ox.ac.uk/fsl/). After that all T1 images were corrected using the SPM2 bias correction and then spatially normalized to the skull-stripped SPM2 template (Montreal Neurological Institute (MNI) space). Normalization parameters were applied to the functional images and then the images were smoothed with an isotropic Gaussian kernel (4 mm full-width at half-maximum, FWHM). Using combined preprocessing for both runs together enabled us to do a direct comparison of the four conditions (words with silence (WoSil), silence (Sil), words with RecSBN (WoRecSBN), and RecSBN).

Statistical analysis of group fMRI data

Data analysis was performed using a General Linear Model as implemented in SPM2 [Friston et al., 1995]. The two experimental runs were treated as one session and four covariates (one for each condition) were calculated by convolving each design with an HRF [see Gaab et al., 2006, for details]. The covariates were WoSil, Sil, WoRecSBN, and RecSBN. In order to adjust for a possible baseline shift, we created the Sil covariate for the entire duration of the two combined runs and applied global normalization as implemented in SPM2. The covariates were then entered as regressors in a group analysis. No condition was specified (regressor-only design), a high-pass filter with a time constant of 128 s was applied, and no basic set was selected. This approach allowed us to create the following contrasts (Fig. 3).

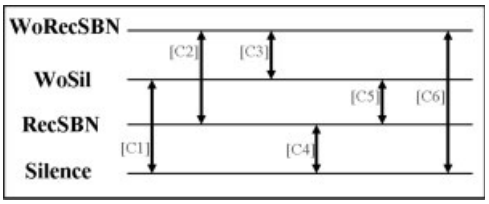

Figure 3.
Performed contrasts: 1) WoSil > Sil; 2) WoRecSBN > RecSBN; 3) WoRecSBN > WoSil; 4) RecSBN > Sil; 5) WoSil > RecSBN; 6) WoRecSBN > Sil.

Contrast 1 [C1]: WoSil > Sil. This contrast shows the effects of listening to words in the absence of SBN vs. listening to silence.

Contrast 2 [C2]: WoRecSBN > RecSBN. C2 shows the effects of listening to words in the presence of SBN vs. listening to SBN. In the absence of SBN effects, C1 should equal C2.

Contrast 3 [C3]: WoRecSBN > WoSil. This contrast shows the effects of listening to words in the presence of SBN vs. listening to words in the absence of SBN.

Contrast 4 [C4]: RecSBN > Sil. C4 shows the effects of listening to SBN vs. listening to silence (within a linear system, C4 should equal C3).

Contrast 5 [C5]: WoSil > RecSBN. This contrast shows the effects of listening to words in the absence of SBN vs. listening to SBN.

Contrast 6 [C6]: WoRecSBN > Sil. This contrast [C6] shows the effects of listening to words in the presence of SBN vs. listening to silence.

All results were corrected for multiple comparisons (family-wise error (FWE) correction; $P < 0.05$; extent: 25).

ROI Delineation

Four anatomically defined regions of interest (ROIs) were chosen for this analysis using the software program WFU_pick Atlas and the implemented AAL atlas [Maldjian et al., 2003, 2004; Tzourio-Mazoyer et al., 2002]. We defined separately for the right and left hemisphere 1) the transverse gyrus (Heschl's gyrus), and 2) the superior temporal gyrus. Six individual contrast images were created for each subject (Fig. 3) using the above-described regressor-only design. ROIs were applied to the contrast images for each subject separately, and region-specific values (weighted parameter estimates) were averaged over all subjects for each of the two designs. Then nonparametric statistical tests (Friedman tests and Wilcoxon tests) were applied in order to assess possible statistical differences between the two experimental conditions as well as hemispheric differences within each experimental design.

Experimental Hypotheses

In addition to the above-described contrasts 1–6, the following hypotheses were tested by comparing the mean weighted parameter estimates of the ROIs.

Hypothesis A: SBN masks auditory response to words (C1 > C2)

As shown in several previous studies [e.g., Gaab et al., 2006; Hall et al., 1999; Shah et al., 1999, 2000], we hypothesized that the contrast WoSil > Sil would reveal greater weighted parameter estimates than the contrast WoRecSBN > RecSBN due to RecSBN-SBN-induced masking of the BOLD response. Furthermore, we hypothesized that this effect will be present in all four ROIs. This comparison is a direct test of the influence of SBN.

Hypothesis B: Signal intensities within Heschl's gyrus and superior temporal gyri will show differences in signal intensities for listening to words compared to listening to SBN (C1 > C4 for left Heschl's gyrus and bilateral superior temporal gyrus and C1 < C4 for right Heschl's gyrus)

We hypothesized that the contrasts WoSil > Sil would reveal greater weighted parameter estimates than the contrast RecSBN > Sil for the ROIs covering left Heschl's gyrus and bilateral superior temporal gyrus. This hypothesis is based on several studies that showed differences between speech and nonspeech stimuli mainly in left lateralized auditory regions and/or bilateral superior temporal regions that are associated with higher-order auditory processing [e.g., Binder et al., 1997, 2000; Poeppel et al., 2004; Zatorre et al., 1992]. Furthermore, we hypothesized an increase in activation within right Heschl's gyrus for RecSBN > Sil compared to WoSil > Sil [Poeppel et al., 2004; Zatorre et al., 1992].

Hypothesis C: There will be increased signal intensities for listening to words in the presence of SBN compared to simply listening to SBN (C6 > C4)

We hypothesized that the contrast WoRecSBN > Sil will reveal greater weighted parameter estimates than the contrast RecSBN > Sil in all four ROIs (see also Hypothesis B). Moreover, differences between the two conditions should be similar to contrast C1.

Hypothesis D: An SBN-contaminated baseline leads to a signal reduction of the response to words (C1 > C5)

We hypothesized that the contrast WoSil > Sil will lead to greater weighted parameter estimates (all ROIs) than the contrast WoSil > RecSBN. This comparison will test the assumption that loss of signal in human auditory cortex is caused by elevated baseline from SBN.

Hypothesis E: There will be no differences in signal intensities when listening to words in the absence of SBN compared to listening to words in the presence of SBN in all 4 ROIs (C6 = C1)

Based on the results from Talavage and Edmister [2004], we hypothesized that the contrast WoRecSBN > Sil will not significantly differ from WoSil > Sil. If this is the case, it will directly demonstrate nonlinearity because otherwise, if the HRF response within auditory cortex is linear, then C6 should be greater than C1 and the difference value between the two should be similar to RecSBN > Sil (C4).

Hypothesis F: A word-contaminated baseline leads to a signal reduction of the response to SBN (C4 > C3)

In accordance with the results demonstrated by Talavage and Edmister [2004], we hypothesized that the contrast RecSBN > Sil will show greater weighted parameter estimates than the contrast WoRecSBN > WoSil due to nonlinearity of the fMRI response in the human auditory cortex, in contradistinction to the case if the system is linear when C4 should equal C3. Furthermore, we hypothesized that this effect will be present in all four ROIs. All hypotheses were tested using ROIs covering left- and right-hemispheric Heschl's gyrus (HL and HR) and ROIs covering the entire superior temporal gyrus in the left and right hemisphere (STGL and STGR). All comparisons were made using paired *t*-tests.

RESULTS

Behavioral Results

The mean accuracy was 80% (standard deviation (SD) = 10.1) for the words task (no RecSBN) and 83% (SD = 12.3) for the words + RecSBN tasks. There was no significant difference for the percent correct answers between the two conditions ($P > 0.5$).

Auditory Setup Results

Subjects chose on average an SPL amplitude of 56.4 (±8.7) dB (A) for the words presented in silence and 74.8 (±4.8) dB (A) for the words presented with SBN. Furthermore, an average SPL of 53.4 (±7.4) dB (A) was chosen for the recorded SBN. The SPL for the SBN was measured as 116 db (A). The isolation of the headphones was not measured but was estimated to be ~35 dB.

Imaging Results

Group analysis

Figure 4 presents results for all six contrasts defined in Figure 3. All results are presented at threshold $P < 0.05$ (corrected for multiple comparisons, FWE, cluster size: 25). In summary, the superior temporal gyrus was activated bilaterally (although to a different degree) in all contrasts except for WoSil > RecSBN. The cingulate gyrus was activated only for the contrasts WoSil > Sil and WoRecSBN > Sil, whereas the caudate nucleus was activated only for WoRecSBN > RecSBN (left) and WoSil > RecSBN (bilateral). The contrast WoSil > Sil showed additional activation of the left precentral gyrus, which was not seen in any other contrast. The right cerebellum was exclusively activated in the contrast WoRecSBN > RecSBN, whereas activation of the left cuneus was only seen for the contrast WoRecSBN > Sil. For activation details, see Table I and Figure 4.

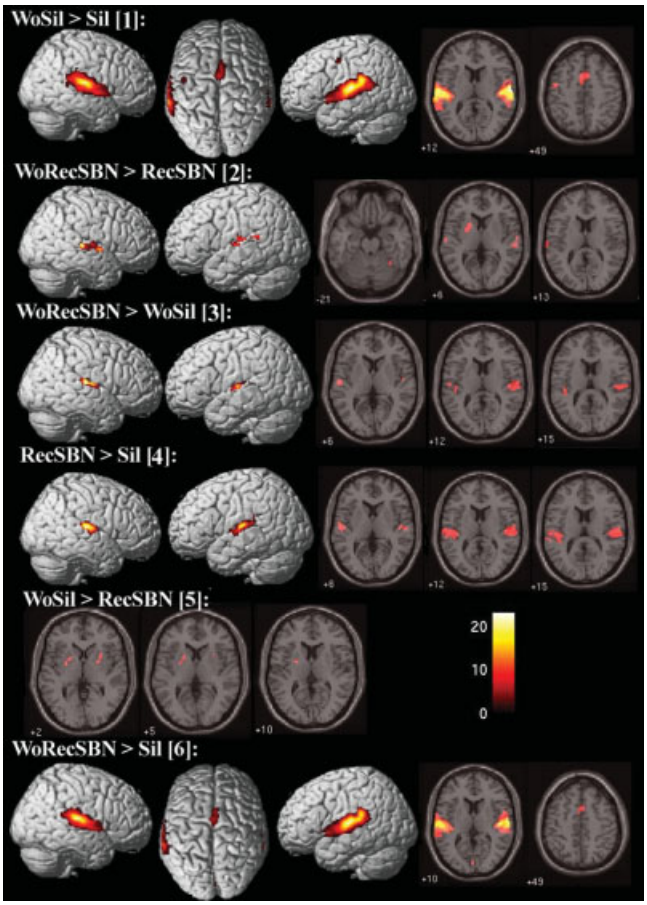

Figure 4.
Imaging results for the six different contrasts ($P < 0.05$, corrected for multiple comparisons, FWE). Each row depicts one of the six different contrasts in either 3D rendering or axial slices (for contrast 5 only) in the left columns. Furthermore, we selected axial slices that show most of the activation reported in Table I (right columns). (See Table I for activation table.) [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

ROI analysis (Fig. 5)

The results for the ROI analysis are shown in Figure 5. We examined the following ROIs: left and right Heschl's gyrus (HL/HR) and superior temporal gyrus (STGL/STGR).

TABLE I. Activation table for the six different contrasts

Region	Extent	MNI coordinates			T
		x	*y*	*z*	
WoSil > Sil [1]					
Right superior temporal gyrus	2255	64	−14	10	13.20
Left superior temporal gyrus	3079	−60	−18	12	19.47
Cingulate gyrus	519	−4	12	44	8.60
Cingulate gyrus	34	−2	−28	32	5.87
Left precentral gyrus	40	−46	−6	48	6.95
WoRecSBN > RecSBN [2]					
Right superior temporal gyrus	129	62	−26	6	8.04
Left caudate nucleus	112	−20	8	4	6.89
Left superior temporal gyrus	25	−64	−42	16	6.20
Left superior temporal gyrus	25	−60	14	8	5.92
Left superior temporal gyrus	33	−66	−24	14	5.76
Right cerebellum	43	36	−52	−20	5.90
WoRecSBN > WoSil [3]					
Left superior temporal gyrus	87	−56	−16	8	7.17
Left superior temporal gyrus	75	−42	−34	16	6.20
Right superior temporal gyrus	223	54	−22	14	7.12
RecSBN > Sil [4]					
Right superior temporal gyrus	445	54	−20	14	8.81
Left superior temporal gyrus	512	−42	−26	16	7.19
WoSil > RecSBN [5]					
Left caudate nucleus	65	−18	8	4	5.77
Right caudate nucleus	28	26	2	2	5.37
WoRecSBN > Sil [6]					
Right superior temporal gyrus	1836	62	−14	10	18.66
Left superior temporal gyrus	2607	−58	−18	10	17.05
Cingulate gyrus	306	2	12	40	7.19
Left cuneus	40	−2	88	6	5.68

All results are reported for $P < 0.05$, corrected for multiple comparisons. MNI, Montreal Neurological Institute; WoSil, words with silence; RecSBN, recorded scanner background noise.

Hemispheric ROI differences

Using Wilcoxon tests, we compared HL and HR as well as STGL and STGR within each of the six contrasts. There was no significant hemispheric difference for any of the six contrasts.

Testing Hypotheses A–F

A summary of results for Hypothesis A–F is presented in Table II.

Hypothesis A. C1 > C2. The Wilcoxon tests revealed significantly higher mean weighted signal estimates for left and right Heschl's gyrus for WoSil > Sil in comparison to WoRecSBN > RecSBN (for HL: Z = –2.19; HR: Z = –2.14; all $P < 0.05$). The ROIs covering the left and right superior temporal gyrus showed a trend for C1 > C2 but significance was not reached (STGL: Z = –1.42; $P = 0.07$ and STGR = Z = –1.78; $P = 0.05$). These results confirm our Hypothesis A: *SBN masks auditory response to words* with this masking being reliable in Heschl's gyrus and bordering on reliability in superior temporal gyrus.

Hypothesis B. C1 > C4 for left Heschl's gyrus and bilateral superior temporal gyrus and C1 < C4 for right Heschl's gyrus. The four Wilcoxon tests showed no significant difference for any of the four ROIs between WoSil > Sil and RecSBN > Sil (all $P > 0.1$). These results do not confirm our Hypothesis B: *Signal intensities within Heschl's gyrus and superior temporal gyri will show differences in signal intensities when listening to words compared to listening to SBN.*

Hypothesis C. C6 > C4. The four Wilcoxon tests showed significantly higher mean weighted signal estimates in left and right superior temporal gyrus (STGL: Z = –2.04, $P < 0.05$; STGR: Z = –2.60, $P < 0.01$). Based on these results we compared the difference between C6 and C4 (C6-C4) with contrast C1 in order to further examine linearity within superior temporal gyri. The results showed no significant differences within superior temporal gyri between [(WoRecSBN > Sil) – (RecSBN > Sil)] and (WoSil > Sil), although a trend was seen for both ROIs towards increased weighted parameter estimates for WoSil > Sil in comparison to [(WoRecSBN > Sil) – (RecSBN > Sil)] (STGL: Z = –1.42, $P < 0.15$ and STGR:Z = –1.83, $P < 0.07$). These results confirm our Hypothesis C: *There will be increased signal intensities for listening to words in the presence of SBN compared to simply listening to SBN* for bilateral superior temporal gyri but not for Heschl's gyri.

Hypothesis D. C1 > C5. The four Wilcoxon tests revealed significantly higher mean weighted signal estimates for left and right Heschl's gyrus for WoSil > Sil in comparison to WoSil > RecSBN (for HL: Z = –2.80; HR: Z = –2.70; all $P < 0.01$). The ROIs covering left and right superior temporal gyrus showed a trend for C1 > C5 but significance was not reached (STGL: Z = –1.88; STGR: Z = –1.88; all $P = 0.059$). These results confirmed *An SBN-contaminated baseline leads to a signal reduction of the response to words* in Heschl's gyrus, but not in STG.

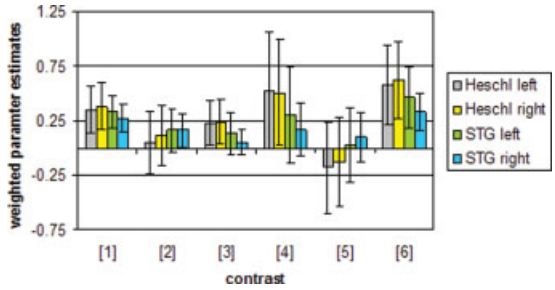

Figure 5.
Results of the ROI analysis for the four ROIs. The following contrasts were examined: 1) WoSil > Sil; 2) WoRecSBN > RecSBN; 3) WoRecSBN > WoSil; 4) RecSBN > Sil; 5) WoSil > RecSBN; 6) WoRecSBN > Sil. All values are weighted parameter estimates. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE II. Result summary for the hypotheses A–F

Hypothesis	Results	Confirmed?
A: Contrast 1 > Contrast 2 [WoSil > Sil] > [WoRecSBN > RecSBN]	C1 > C2 in Heschl's gyrus (bilateral); trend in bilateral STG	Yes for Heschl's gyrus
B: Contrast 1 >/< Contrast 4 [WoSil > Sil] >/< [RecSBN > Sil]	C1 = C4 for all ROIs	No
C: Contrast 6 > Contrast 4 [WoRecSBN > Sil] > [RecSBN > Sil]	C6 > C4 in STG (bilateral); also trend in STG (bilateral) for [(C6–C4) < C1]	Yes for STG
D: Contrast 1 > Contrast 5 [WoSil > Sil] > [WoSil > RecSBN]	C1 > C5 in Heschl's gyrus (bilateral); trend was seen in bilateral STG	Yes for Heschl's gyurs
E: Contrast 6 = Contrast 1 [WoRecSBN > Sil] = [WoSil > Sil]	C6 > C1 in Heschl's gyrus (bilateral); trend in left STG	Yes for STG
Follow up on E: (Contrast 6 – Contrast 1) = Contrast 4 ([WoRecSBN > Sil] – [WoSil > Sil]) = RecSBN > Sil)	[(C6–C1)] < C4 in Heschl's gyrus (bilateral); trend in right STG	Yes for Heschl's gyrus
F: Contrast 4 > Contrast 3 [RecSBN > Sil] > [WoRecSBN > WoSil]	C4 > C3 in Heschl's gyrus (left and right); trend in STG (bilateral)	Yes for Heschl's gyrus

WoSil, words contrasted with silence; RecSBN, recorded scanner background noise; WoRecSBN, words contrasted with silence; Sil, silence; ROI, region of interest; STG, superior temporal gyrus.

Hypothesis E. C6 = C1. The four Wilcoxon tests showed significantly higher mean weighted signal estimates for left and right Heschl's gyrus for WoRecSBN > Sil in comparison to WoSil > Sil (for HL: Z = –2.70; HR:Z = –2.80; all $P < 0.01$). The ROI covering left superior temporal gyrus showed a trend for C6 > C1 but significance was not reached (STGL: Z = −1.78; $P < 0.1$). Based on these results, Hypothesis E: *There will be no differences in signal intensities when listening to words in the absence of SBN compared to listening to words in the presence of SBN* has only been confirmed for STG.

A follow-up contrast that compared the difference between C6 and C1 (C6-C1) with contrast C4 was tested in order to further examine nonlinearity within auditory areas. The results showed increased weighted parameter estimates in Heschl's gyri for RecSBN > Sil in comparison to the difference C6-C1 (HL: Z = –2.19; HR = –2.09; all $P < 0.05$). No differences were found within STG (STGL: Z = –1.42 $P > 0.1$; STGR: Z = –1.837; $P > 0.05$), although a trend could be observed in right STG.

Therefore, we can conclude that although there are differences in signal intensities when listening to words in the absence of SBN compared to listening to words in the presence of SBN, these differences are smaller than signal intensities evoked by RecSBN > Sil. This follow-up result shows clearly the nonlinearity of auditory cortices.

Hypothesis F. C4 > C3. The four Wilcoxon tests showed significantly greater mean weighted signal estimates in left and right Heschl's gyrus for RecSBN > Sil in comparison to WoRecSBN > WoSil (HL = –2.19 and HR = –2.09, $P < 0.05$). The results showed no significant differences within superior temporal gyri, although trends were seen for both ROIs (STGL = –1.47, $P < 0.15$, and STGR = −1.93. $P < 0.06$). These results confirm Hypothesis F: *A word-contaminated baseline leads to a signal reduction of the response to SBN* for Heschl's gyrus, with a weaker suggestion that the hypothesis may apply to the superior temporal gyrus.

DISCUSSION

This study demonstrated the influence of recorded SBN (RecSBN) on fMRI activation within primary and higher-order auditory regions by directly comparing two experimental sessions with exactly the same auditory stimulation (an active verbal working memory task), which was presented either with or without RecSBN. In accordance with previous studies [Talavage and Edmister, 2004], our results suggest that SBN-induced masking of the BOLD response in experimental designs that employ continuous SBN might be caused by a combination of raised baseline levels and nonlinearity within auditory cortices. By comparison with the method of Talavage and Edmister [2004], who varied the amount of SBN in a block design, we employed a sparse temporal sampling technique with varying delay times between auditory stimulation and image acquisition, which allowed us to compare word processing in the absence and presence of SBN. These conditions were then compared to an SBN-contaminated baseline or silence. Furthermore, we used an active verbal memory task with higher cognitive demands in comparison to Talavage and Edmister [2004], who employed a passive music-listening task. In addition, we obtained 30 slices covering the entire brain, which enabled us to assess the influence of SBN outside of primary auditory cortices.

Our results show that adding recorded SBN to an experimental condition (e.g., a word sequence) does not alter

signal intensities to the same degree as SBN does when presented with a silent background. This results in a decrease of signal intensity when comparing an SBN-contaminated experimental and control condition. Effects of SBN-induced masking were observed mainly in primary auditory cortices, but also, although to a lesser degree, within superior temporal cortices. However, recorded SBN may not be equivalent to real SBN when testing effects of SBN on auditory processing, since the real SBN is conducted via head and body as well as accompanying vibrations. In fact, the optimal approach would be to modify the pulse sequence to generate real SBN instead of recorded SBN by turning off the RF pulse (to avoid perturbing the NMR equilibrium) and playing the gradient pulses [Bandettini et al., 1998]. We were unable to do that for this study. Nevertheless, we expect influences of these effects on signal intensities within auditory cortices to be minimal since subjects established sound levels that had perceived similarity across conditions.

Effects of SBN-Induced Masking of the BOLD Response within Auditory Regions

Several studies assessed the influence of "real" or recorded SBN on auditory processing and found increases in signal intensities in the "silent" designs with longer TRs in comparison to the conventional designs with increased SBN [e.g., Baumgart et al., 1996; Gaab et al., 2006; Hall et al., 1999; Shah et al., 1999, 2000; Yetkin et al., 2003]. Our results support these findings. Although both contrast WoSil > Sil (C1) and WoRecSBN > RecSBN (C2) revealed activation of bilateral superior temporal gyrus, an ROI analysis showed significant signal decreases for the comparison employing RecSBN in bilateral Heschl's gyrus. Since only a (nonsignificant) trend was observed for the superior temporal gyri, our Hypothesis A (C1 > C2) was only confirmed for Heschl's gyri.

Our result is especially interesting since the average spectral energy of the two stimulus classes (words and RecSBN) overlap only moderately (Fig. 2). Several studies suggested increased SBN-induced masking with increased similarities between spectral content of tone stimulus and SBN [e.g., Langers et al., 2005; Scarff et al., 2004], and Talavage and Edmister [2004] suggest that their observed nonlinearity of the fMRI response within auditory regions might be due to spectral overlap of the stimuli used in their experiment. Our results show that choosing a frequency different from the SBN does not circumvent or avoid effects of SBN-induced masking of the BOLD response when using a higher-order auditory task.

The SBN-induced masking effect revealed here is less profound in areas that are involved in higher-order auditory processing (STGL and STGR), as also shown by Gaab et al. [2006]. Additionally, we observed no hemispheric differences within either of the two comparisons. Several studies examined activation of auditory cortex using speech and nonspeech stimuli within auditory areas. Most of these studies showed a strong left-lateralization network for speech stimuli in several regions such as superior temporal gyrus and mostly in the superior temporal sulcus [e.g., Binder et al., 1997, 2000; Giraud and Price, 2001; Poeppel et al., 2004]. In our study we examined hemispheric differences only in Heschl's and superior temporal gyri, which could be one reason for the lack of a lateralization effect due to the limitations of our ROI analysis. Furthermore, our subjects were asked to perform a same/different judgment. This task does not require higher-order cognitive processing of the words themselves and therefore our subjects might have made their judgments more based on acoustical features or sound analysis. However, Hermann et al. [2000] showed lateralization effects of SBN only on early auditory but not early linguistic processing.

Overall, our results suggest that the SBN influences primary as well as higher-order auditory areas but to a different degree.

RecSBN-Induced Activation within Auditory Regions

The nature of our experimental design further enabled us to assess the RecSBN-induced activation in greater detail. Contrasting the two baselines (RecSBN > Sil; contrast C4) revealed bilateral activations of Heschl's gyrus and the planum temporale. This finding is in accordance with previous studies assessing neural correlates in response to "real" or recorded SBN using various methods and tasks [e.g., Hall et al., 2000; Mathiak et al., 2002; Novitski et al., 2001, 2003; Ulmer et al., 1998]. However, we did not observe a lateralization effect within auditory areas for listening to RecSBN, although several studies suggest increased right-lateralization in response to sounds that may be related to SBN, such as noise bursts [Zatorre et al., 1992], frequency modulated tones [Poeppel et al., 2004], or deviant gradient switching of recorded scanner noise [Mathiak et al., 2002]. In our study, subjects were not explicitly asked to attend to the scanner noise and this could be one explanation for the lack of lateralization. One possible confound in our study is the fact that we had two separate experimental runs. Differences between the two baselines (Sil and RecSBN) could be due to either RecSBN-induced activity, baseline shifts, or differences in the perceptual or cognitive demands for the two baselines. However, we performed baseline normalizations, which should reduce this issue. Furthermore, within one experimental run Talavage and Edmister [2004] contrasted an extended duration of acoustic imaging noise with a short duration of acoustic noise in the absence of an auditory stimuli and showed mean signal changes for extended compared to short noise duration within auditory regions.

We compared the contrasts WoSil > Sil and RecSBN > Sil in terms of weighted parameter estimates within auditory areas (Hypothesis B, C1 $\neq$ C4). The statistical analysis of the ROIs revealed no significant difference between the two contrasts and therefore does not confirm our Hypothe-

sis B. As previously discussed, this could be due to the chosen ROIs and/or nature of the experimental task. Furthermore, this hypothesis has not been tested previously using recorded SBN, which may have had an effect on the outcome. One explanation could be the different amplitude levels of words and RecSBN in this task. Our subjects were asked to choose the amplitude of the three auditory stimuli types in order to achieve "perceptual similarity." This may have led to amplitude-based differences between the conditions. However, studies showing an influence of amplitude within auditory regions demonstrate increased activation and spatial extent in response to increased amplitude [e.g., Jancke et al., 1998; Lasota et al., 2003]. Therefore, stimulus presentation with a higher amplitude during the RecSBN condition might have led to a positive advantage for the RecSBN condition compared to the condition without RecSBN. However, whether increased amplitude leads to increased spatial extent and signal intensity for all auditory stimuli is still in debate [Hall et al., 2001; Jancke et al., 1998].

We further examined a possible difference between the contrasts WoRecSBN > Sil and RecSBN > Sil (Hypothesis C, C6 > C4) and revealed greater weighted parameter estimates for WoRecSBN > Sil in comparison to RecSBN > Sil in superior temporal but not Heschl's gyri. Since similar amplitude levels were chosen for the RecSBN stimuli in this comparison, it is less likely that this lack of significance in Heschl's gyri is due to increased amplitude levels in the contrast RecSBN > Sil. It seems more likely that the effect is due to nonlinearity effects within auditory areas, as proposed by Talavage and Edmister [2004], which will be further discussed below. However, the effects in superior temporal gyri are in accordance with previous studies comparing speech and noise stimuli that revealed increased involvement of higher-order auditory areas in speech than noise processing [e.g., Binder et al., 2000; Giraud and Price, 2001; Zatorre et al., 1992]. Nevertheless, if the signals within STG add up linearly then the difference between WoRecSBN > Sil and RecSBN > Sil should be as great as the contrast WoSil > Sil, but our analysis shows a trend towards increased weighted parameter estimates for WoSil > Sil in comparison to [(WoRecSBN > Sil) – (RecSBN > Sil)], which can be explained by nonlinearity within STG and will be further discussed below.

Source of SBN-Induced Masking of the BOLD Response

Several authors have discussed the origin of the neural masking in auditory experiments with continuous SBN [e.g., Edmister et al., 1999; Hall et al., 1999; Langers et al., 2005; Scarff et al., 2004; Shah et al., 1999; Talavage et al., 1999, 2004]. SBN-induced masking of the BOLD response is defined as a reduction of the signal intensities or spatial spread within auditory areas as a result of differences of the SBN-induced activation in the experimental and control condition. Most of these studies suggest SBN-induced masking or nonadditive effects of fMRI gradient noise as a result of comparing the raised "baseline" signal (or OFF period) to one or more experimental conditions (or ON periods) which might lead to reduced sensitivity to stimulus-induced signal changes due to this "inflated scanner-induced baseline" [e.g., Mazard et al., 2002; Scarff et al., 2004; Talavage et al., 1999]. Additionally, Edmister et al. [1999] suggests nonadditive effects between SBN and auditory stimuli as well as interference between the two stimuli that result in partial saturation of the HRF within auditory areas, whereas Hall et al. [1999] stated that signal increases during sparse designs are the result of greater T2*-weighted signal due to increased signal recovery between excitations. Nonlinear interaction between different tone stimuli which show a similar timing with the HRF itself and therefore result in saturation effects within auditory areas were reported by Langers et al. [2005]. These interactions were stronger and more complex when the spectral content of the tone stimulus and the SBN were more similar. The authors state that these interactions seem to be caused mainly by "physiological limitations at a vascular level." In summary, all studies seem to agree upon influences of raised baseline levels as a possible source for SBN-induced masking of the BOLD response but no direct hypothesis test was performed in their studies.

This hypothesis test was the aim of a study by Talavage and Edmister [2004]. The authors propose that the reduced activation in designs with increased SBN might be caused by the fact that the HRF in response to experimental stimuli and SBN may not add in a linear fashion and that therefore statistically contrasting the two may lead to reduced significance. However, the major difference between our and their study is the fact that we employed a silent baseline with absolutely no SBN contamination, whereas Talavage and Edmister [2004] varied the amount of SBN contamination in several steps. Furthermore, their subjects were asked to attend to either music or SBN but no active task was performed, whereas subjects in our study were actively engaged in the verbal working memory task and were not explicitly asked to attend to the SBN (which is more like a standard fMRI study in which subjects attend to and respond to stimuli rather than SBN). Despite these differences in design, their study agrees qualitatively with the present results.

Our Hypothesis D (C1 > C5) examines the assumption that an SBN-contaminated baseline results in signal decreases within auditory regions. We tested this assumption using a silent as well as an SBN-contaminated baseline and compared our contrast C1 (WoSil > Sil) to contrast C5 (WoSil > RecSBN) and found decreased weighted parameter estimates in the contrast with the SBN-contaminated baseline in bilateral Heschl's gyrus. A clear but nonsignificant trend was seen for bilateral superior temporal gyrus. These results provide evidence for the assumption that a raised baseline level is one source of SBN-induced masking of the BOLD response.

Hypothesis E (C6 = C1) further examines the proposed nonlinearity of the HRF in the human auditory cortex. We compared the weighted parameter estimates for the contrasts WoSil > Sil [C1] with WoRecSBN > Sil [C6] and revealed increased weighted parameter estimates for WoRecSBN > Sil in comparison to WoSil > Sil within Heschl's gyri but not STG. However, when comparing the difference between these two conditions with RecSBN > Sil, the results showed increased parameter estimates for RecSBN > Sil in comparison to (WoRecSBN > Sil)-(WoSil > Sil). This is strong evidence for nonlinearity of the HRF in auditory cortex. If the signal within auditory cortex would be linear then the amount of signal increase due to added RecSBN to the words should be as great as contrasting RecSBN with a silent baseline. Our results are in accordance with Talavage and Edmister [2004], who showed no effect when raising the quantity of SBN in a condition with auditory stimulation and comparing it to a nonstimulus condition with constant SBN.

In addition to the follow-up contrast of Hypothesis E we found a significant difference of the weighted parameter estimates for RecSBN > Sil in comparison to WoRecSBN > WoSil (Hypothesis F, C4 > C3) within Heschl's gyri and as a trend for both superior temporal gyri. If the signal within auditory cortices would be linear, then the two contrasts should not differ significantly (see also Hypothesis E). This hypothesis supports the assumption of nonlinearity within primary auditory cortex as well as the proposed increase of baseline levels as a possible source of SBN-induced masking of the BOLD response.

Overall, our results suggest that the source of neural masking (Hypothesis A) is a combination of raised baseline levels (Hypothesis D, F) and nonlinearity within auditory cortices (Hypotheses B, C, E, F). Signal intensities in response to RecSBN seem to differ when 1) RecSBN is contrasted with a silent baseline and 2) added to an experimental condition (e.g., word sequences) resulting in SBN-induced masking effects when contrasted with each other. Since the experimental conditions in this study were identical except for presenting RecSBN during the 4 s of words, activation differences between the two conditions cannot be attributed to differences in the overall task or the presentation of continuous SBN and its effect on sustained attention.

SBN-induced masking varies by cortical area with the greatest effect being observed in Heschl's gyri but is also present in superior temporal gyri.

Extratemporal Areas and RecSBN

Most studies examining the influence of SBN on auditory processing focused on possible signal changes within auditory areas. By examining the whole brain we were able to assess the influence of SBN on nonauditory areas. Our contrast WoSil > Sil (contrast C1) revealed additional activation of precentral gyrus as well as anterior cingulate for the chosen threshold. Contrasting WoRecSBN with RecSBN revealed additional activation of left caudate nucleus and right cerebellum. We did not directly compare the two scans but if the RecSBN has no influence on nonauditory areas then similar network components should be seen. Further studies are needed to assess whether SBN- or RecSBN-induced masking of the BOLD response also occurs in extratemporal areas [see also Gaab et al., 2006].

CONCLUSION

Our study demonstrates that raised baseline levels as well as nonlinearity within auditory cortices are the key sources for SBN-induced masking of the BOLD response in experimental designs employing continuous SBN. This was tested using a sparse temporal sampling design and adding recorded SBN (RecSBN) to half of the experimental trials. The lack of SBN during half of our auditory stimulation trials allowed for the first time a direct comparison of verbal auditory processing in the presence and absence of SBN. Masking of the BOLD response in the presence of SBN was observed mainly in primary auditory cortices but was also observed within the entire superior temporal cortices. These results should be taken into account when designing auditory experiments within the MR-environment and when interpreting auditory activations that were obtained in the presence of continuous SBN. However, in addition to our jittered sparse temporal sampling method, other "silent" designs should be considered during the experimental design phase [for review, see Amaro et al., 2002].

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