The Effect of MR Scanner Noise on Auditory Cortex Activity using fMRI

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Abstract: Auditory functional magnetic resonance imaging (fMRI) studies are limited by the presence of noise produced by echo planar imaging (EPI). The current study quantifies the effect of MR scanner noise on psychophysical measures of the perception of loudness and on measures of tonotopy, the representation of auditory frequencies within the auditory cortex. Seven normal hearing adults were examined using tones of 5 different auditory frequencies (250, 500, 1,000, 2,000, 4,000 Hz) of equal loudness. Using an imaging protocol with peak MR scanner noise at 1,460 Hz, the perception of loudness and detectable fMRI activity in response to a 1-kHz tone was less compared to other frequencies. When the imaging protocol was changed such that peak MR scanner noise occurred at 2,080 Hz, the perception of loudness and detectable fMRI activity in response to a 2-kHz tone was less compared to other frequencies. The reduction in the measured fMRI activity for tones near scanner frequencies may be due to an inflated scanner-induced baseline at those frequencies. In addition, fMRI activity decreased with increasing frequency, possibly due to the upward spread of masking of low-frequency, high-intensity tonal stimuli or the proximity of low-frequency core and belt areas of the auditory cortex. These results demonstrate the direct effect of scanner noise and high-intensity tonal stimuli on measurements of auditory cortex tonotopy. *Hum. Brain Mapp.* 22:341–349, 2004. © 2004 Wiley-Liss, Inc.

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INTRODUCTION

The noise generated by a magnetic resonance (MR) scanner is a major limitation faced by functional magnetic resonance imaging (fMRI) studies of the auditory system [Bardettini and Wong, 1997; Belin et al., 1999; Hall et al., 1999; Ulmer et al., 1998]. The high-intensity noise is due to the flexing of gradient coil loops in a magnetic field as current passes through the loops during imaging [Cho et al., 1997; Counter et al., 1997; Shellock et al., 1998]. Even in the absence of scanner noise, the liquid helium circulation pump and the air ventilation systems produce low-level noise that is continuously present in the magnet room [Ravicz et al., 2000]. Although MR scanner noise contains many audible frequencies, the main power of the noise energy occurs at ~1

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kHz with higher order resonances of lower intensity [Bilecen et al., 1998a; Ravicz et al., 2000]. This noise can reduce activity within the auditory system through psychophysiological masking [Edmister et al., 1999; Van de Moortele et al., 1998], habituation, saturation, and high-level processing due to the necessity to attend to more than one sound at a time [Belin et al., 1999]. This makes functional imaging studies of the auditory system a challenging task.

Imaging protocols have been developed to address these issues including sparse sampling [Van de Moortele et al., 1998] or silent [Edmister et al., 1999] fMRI, where imaging sequences are completed in clusters separated from each other by long silent periods (i.e., 10 sec or longer) such that auditory stimuli are relatively free of scanner noise. These paradigms are not without limitations, however, including their reduced temporal efficiency and resolution due to infrequent scanning [Edmister et al., 1999; Hall et al., 1999; Melcher et al., 1999].

It is widely accepted that the auditory cortex is arranged topographically [Talavage et al., 2000], with adjacent neurons and groupings of neurons representing adjacent auditory frequencies. This manner of organization is referred to as *tonotopy*. Studies lending support for auditory tonotopy in humans include single-unit activity recordings [Howard et al., 1996, 2000], sound-evoked magnetic and electric responses measured at the head surface [Lütkenhöner and Steinsträter, 1998; Mühlhölzer et al., 1998; Pantev et al., 1988, 1990, 1994, 1995; Romani et al., 1982; Yamamoto et al., 1988], positron emission tomography (PET) [Lauter et al., 1985; Lockwood et al., 1999], as well as fMRI [Bilecen et al., 1998b; Formisano et al., 2003; Le et al., 2001; Talavage et al., 2000; Wessinger et al., 1997; Yang et al., 2000]. Although most fMRI studies have shown that low-frequency activation sites are more lateral and anterior than high-frequency sites, results regarding the anterior/posterior representation of frequency have been inconclusive, possibly due to overlapping areas of the auditory cortex within the image voxels (i.e., partial voluming) [Wessinger et al., 1997].

To date, the exploration into the effects of MR scanner noise on fMRI studies of auditory cortex has been limited to discussion. In this study, we used psychophysics and fMRI to measure the physiological response to MR scanner noise as it interacts or interferes with the response to auditory tonal stimuli. The goal of the current study was to quantify this effect when the frequency content of the MR scanner noise is known.

SUBJECTS AND METHODS

Subjects

Seven right-handed young adult volunteers from the academic environment of the University of Calgary gave written informed consent to act as subjects in this study. Before the fMRI session, subjects were screened for normal hearing by a certified audiologist at the University of Calgary Clin-

ical Auditory Research Laboratory. Hearing tests included visual otoscopy, acoustic immittance, and pure tone air conduction audiometry between 250 and 8,000 Hz. Audiometric findings confirmed normal hearing sensitivity for all subjects.

Auditory Stimuli

Auditory stimuli consisted of single frequency tones (250, 500, 1,000, 2,000, or 4,000 Hz) created using Matlab v. 6.0 (The Mathworks, Natick, MA). Tonal rise time was 7.5 msec, plateau time was 1.6 sec, and decay time was 7.5 msec. The sampling rate was 44,100 Hz. Stimuli were presented in WAV file format through MR Vision 2000 Ultra Headphones (Resonance Technology, Parthenia, CA) using Presentation software (Neurobehavioral Systems, online at <http://nbs.neuro-bs.com/>) running on a 733-MHz Pentium III computer equipped with a Creative Labs AWE64 sound card. The headphones also helped to attenuate scanner noise. Prior to fMRI, the WAV sound files were set to 85 dB SPL as measured with a Quest Electronics Model 1800 Precision impulse integrating sound level meter (SLM) and a Bruel and Kjaer ear calibrator and headphone coupler using the A-weighted linear scale for each frequency and for both the left and right channels. Since not all frequencies are perceived by humans to be equally loud [Moore, 1995], auditory stimulus levels were adjusted to be perceptually equal in loudness.

MR Imaging Protocols

All imaging experiments were performed using a 3 Tesla MR scanner (General Electric, Waukesha, WI). Sagittal localizer images were obtained to prescribe, for functional imaging, oblique coronal slices through the superior temporal lobe to fully encompass the primary auditory cortex. T₁-weighted images of the prescribed slices were also acquired for anatomical registration of the functional data. T₂*-weighted images were obtained using one of two gradient-recalled echo planar imaging (GRE-EPI) protocols each having different MR scanner noise characteristics (Protocol 1: repetition time, TR = 500 msec; echo time, TE = 30 msec; matrix = 64 × 64; 62.5-kHz receiver bandwidth; field of view (FOV) = 240 × 240 mm; 6 slices; slice thickness = 5 mm. Protocol 2: repetition time, TR = 750 msec; echo time, TE = 30 msec; matrix = 96 × 96; 100-kHz receiver bandwidth; field of view (FOV) = 240 × 240 mm; 9 slices; slice thickness = 5 mm. See MR Scanner Noise Measurements below for noise spectra details).

MR Scanner Noise Measurements

Noise measurements of Protocol 1 and Protocol 2 were made using the SLM connected to a Toshiba Satellite 3000 laptop computer. To minimize the influence of the MR scanner on the magnet within the SLM microphone, the SLM was held at the door of the scanning room and directed

Figure 1.

Frequency spectra of MR scanner noise produced during imaging Protocol 1 (TR/TE = 500/30 msec; 64×64 ; 62.5-kHz receiver bandwidth; FOV = 240×240 mm; 6 slices; slice thickness = 5 mm) and Protocol 2 (TR/TE = 750/30 msec; 96×96 ; 100-kHz receiver bandwidth; FOV = 240×240 mm; 9 slices; slice thickness = 5 mm). The highest peaks in each spectrum occur at 1,460 Hz (Protocol 1) and 2,080 Hz (Protocol 2) (normalized to 0 dB at 1,000 Hz).

towards the MR scanner. Sixty seconds of MR scanner noise was recorded for each Protocol and saved in WAV format using Matlab. A frequency spectrum of the recorded scanner noise was obtained for each Protocol by performing a discrete Fast Fourier Transform and calculating the resulting frequency component magnitudes. As shown in Figure 1, for Protocol 1 (i.e., 64×64 , 62.5-kHz bandwidth), the spectral peak of the MR scanner noise was located at 1,460 Hz. For Protocol 2 (i.e., 96×96 , 100-kHz bandwidth), the spectral peak of the MR scanner noise was located at 2,080 Hz.

Psychophysics Experiment

While in the MR scanner and prior to fMRI, subjects performed a behavioral experiment aimed at determining their perception of loudness of each tone. Tones were presented in random pairs with each frequency paired with another a total of 5 times. The first tone was presented, followed by a 0.5-sec gap, followed by the second tone. Subjects were visually cued to the presentation of each tone and each new trial through an MR Vision 2000 Ultra liquid crystal display visor (Resonance Technology) worn while in the MR scanner. Subjects were instructed to choose the tone they perceived as louder by pressing the appropriate button on a response pad. The next trial commenced 1 sec after the subject made their choice. Subjects were instructed to attend to the loudness of the stimuli rather than the frequency. The

experiment was performed two times, once with MR scanner noise as generated by Protocol 1 and once with MR scanner noise as generated by Protocol 2.

fMRI Experiment

Each subject was imaged using Protocol 1 and again using Protocol 2 within the same imaging session. The fMRI experiment consisted of randomized binaural presentations of the 5 auditory frequencies a total of 4 times each, occurring every 15 sec (20 presentations in total). All auditory stimuli were in the presence of MR scanner noise. Subjects were asked to fixate at all times on a small red dot located at the center of a visual display as seen through the liquid crystal display visor. The red fixation dot changed to green 1 sec prior to the presentation of an auditory stimulus as a visual cue to the presentation of a tone.

Data Analysis

For the behavioral data, the percentage of trials where each frequency was perceived as being louder than another frequency was calculated for each experimental run (i.e., MR noise generated by Protocol 1 and MR noise generated by Protocol 2). MR data were reconstructed as images and corrected for head motion using AIR v5.0 [Woods et al., 1998]. Image voxel time courses were high-pass filtered in the temporal frequency domain to remove low temporal frequency oscillations due to magnetic field drift. The resulting image data set was then analyzed as described below using *Stimulate 5.9* (CMRR, University of Minnesota, Minneapolis, MN).

First, auditory cortex was functionally localized by identifying image voxels exhibiting a significant increase in MR signal in response to a tone regardless of auditory stimulus frequency. These voxels were considered a template for further analysis. This was accomplished using the following procedure. A copy of the functional image data set was subjected to a Gaussian filter (6-mm kernel) to spatially blur the frequency specificity of the auditory responses. Significantly activated voxels were then determined by correlating the time course of image intensity of each image voxel with a hemodynamic response function (HRF) generated by convolving the boxcar nature of stimulus presentation (i.e., 20 repeats of 1.6 sec ON, 13.4 sec OFF) with an ideal HRF in response to a 1-sec stimulus [Birn et al., 2002]. A correlation threshold of $r = 0.4$ was chosen with 8-voxel clustering to get rid of spurious voxels. This result provided a template of voxels within auditory cortex exhibiting a significant response to a stimulus regardless of auditory frequency.

For the remaining analyses, the original un-blurred data set was used to examine the auditory frequency response of each image voxel within the auditory cortex template. First, the "amount of significant activity" within the template in response to each frequency was determined. This provided a measure of the response to each frequency within the entire auditory cortex. Activated voxels for each frequency were found using a two-tailed *t*-test to determine if the average MR signal of a voxel within a narrow time window encompassing

Figure 2.

Behavioral data showing the percentage of trials in which an audible tone was determined to be louder than a paired tone in the presence of magnet noise for (A) Protocol 1 (peak = 1,460 Hz) and (B) Protocol 2 (peak = 2,080 Hz). Data points represent the

average responses of single participants at a particular frequency. The curve is a fitted spline through the average of all participants at each frequency. The dashed line indicates the frequency location of MR scanner noise.

the peak of the fMRI response was significantly greater than during the baseline period immediately prior to the next stimulus presented. Each time window of images contained two temporally-independent images (i.e., greater than 6 sec apart). Hence, for four stimulus presentations, there were seven degrees of freedom. A statistical threshold of $t(7) = 4.0$ ($P = 0.005$) was chosen. The “amount of activity” in response to a particular frequency was then calculated as the product of the number of activated voxels and the percentage increase in MR signal within those voxels.

Next, to calculate the tonotopicity of activated voxels, the magnitude of the fMRI response (measured as a percentage increase in MR signal relative to baseline) was calculated at each auditory frequency for each voxel in the template. Voxels were sorted into populations corresponding to the frequency at which the maximum response was observed (i.e., the “best” frequency was determined for each voxel). The number of voxels at each frequency was recorded.

RESULTS

Psychophysical Results

The behavioral data in Figure 2 show the percentage of trials in which a tone was perceived as louder than other frequencies. A 2-way repeated measures ANOVA detected a significant difference as a function of frequency between Protocol 1 and Protocol 2 (Protocol-frequency interaction: $F = 4.33$, $P = 0.009$). A paired t -test at each frequency revealed a significant difference in the behavioral responses between

Protocol 1 and Protocol 2 at 2000 Hz ($p = 0.017$). There was also a trend at 1000 Hz ($P = 0.075$). There was also a significant bias to choose higher frequencies as being louder regardless of the imaging Protocol (frequency effect: $F = 4.00$, $P = 0.013$). Comparing means revealed a significant difference between 250 and 4,000 Hz ($P < 0.001$), and between 2,000 and 4,000 Hz ($P = 0.001$), corrected using the Tukey correction for multiple comparisons.

fMRI Results

“Amount of fMRI activity” at each frequency

Figure 3A and B show the “amount of significant activity” at each frequency within the auditory cortex for imaging Protocols 1 and 2, respectively. That is, Figure 3A and B is concerned with all voxels that respond to each frequency. A 2-way repeated measures ANOVA detected a significant difference as a function of frequency between Protocol 1 and Protocol 2 (Protocol-frequency interaction: $F = 4.28$, $P = 0.009$). A paired t -test at each frequency revealed a significant difference between Protocol 1 and Protocol 2 at 2,000 Hz ($P = 0.0039$) and a trend at 1,000 Hz ($P = 0.052$). There was also a significant bias of the fMRI response towards lower frequencies regardless of the imaging Protocol (frequency effect: $F = 14.93$, $P < 0.001$). Comparing means revealed a significant difference between 250 and 1,000 Hz ($P = 0.0026$), 2,000 Hz ($P < 0.0001$), and 4,000 Hz ($P = 0.044$), as well as between 500 and 2,000 Hz ($P = 0.015$), corrected using the Tukey correction for multiple comparisons.

Figure 3.

A,B: Activity within the auditory cortex (number of activated voxels, $t > 4.0$, times percentage increase in MR signal above baseline) for all subjects using (A) imaging Protocol 1 (peak = 1,460 Hz) and (B) imaging Protocol 2 (peak = 2,080 Hz). Data points represent the fMRI response from single participants at a particular frequency. The curve is a fitted spline through the average of all participants at each frequency. **C,D:** Proportion of

“best” frequency voxels in fMRI maps of auditory cortex activity obtained using imaging Protocol 1 (C) (peak = 1,460 Hz) and Protocol 2 (D) (peak = 2,080 Hz). Data points represent single participants at a particular frequency. The curve is a fitted spline through the average of all participants at each frequency. The dashed line indicates the frequency location of MR scanner noise.

Proportion of “best frequency” voxels by frequency

Figure 3C and D show the proportion of voxels most highly activated at each frequency (i.e., proportion of “best frequency” voxels) for imaging Protocol 1 and Protocol 2, respectively. A two-way repeated measures ANOVA detected a significant difference as a function of frequency between Protocol 1 and Protocol 2 (Protocol-frequency interaction: $F = 6.03$, $P < 0.001$). A paired t -test at each frequency revealed a significant difference in tonotopic vox-

els between Protocol 1 and Protocol 2 at 1,000 Hz ($P = 0.007$) and 2,000 Hz ($P = 0.039$). There was also a significant bias of tonotopic voxels towards lower frequencies regardless of the imaging Protocol (frequency effect: $F = 14.93$, $P < 0.001$). Comparing means revealed a significant difference between 250 and 1,000 Hz ($P < 0.001$), 2,000 Hz ($P < 0.001$), and 4,000 Hz ($P = 0.0022$), as well as between 500 and 1,000 Hz ($P < 0.001$), 2,000 Hz ($P < 0.001$), and 4,000 Hz ($P = 0.038$), corrected using the Tukey correction for multiple comparisons.

Figure 4.

Representative functional maps of tonotopicity for two participants during Protocol 1 (**A**) and for four participants during Protocol 2 (**B,C**) overlaid on oblique coronal structural MR images through the superior temporal lobe, which are in the same imaging planes as the prescribed functional images. Colored voxels represent the frequency of highest activation (right hemisphere is on left side of image).

Tonotopic Mapping

Based on these results, tonotopic maps were created excluding fMRI responses to auditory frequencies near scanner noise peak frequencies. Tonotopic maps of repre-

sentative slices through auditory cortex are shown in Figure 4A for two representative participants in Protocol 1, and in Figure 4B and C for four different participants in Protocol 2.

DISCUSSION

MR Scanner Noise

To aid in the interpretation of our results, we obtained a measure of the noise characteristics of the MR scanner. The scanner noise peak shifted upwards in frequency from Protocol 1 to Protocol 2, in good agreement with previous reports [Ravicz et al., 2000]. The main scanner noise peaks were located in proximity to tested audible frequencies (1,000 and 2,000 Hz), suggesting that these peaks had a major influence on our results. It is important to note our scanner noise recordings were taken just inside the door of the MR scanner room, not at the magnet bore. Reflection of sound waves in the room and the absence of noise-attenuating headphones for our recordings may have contributed to noise spectra that had more high-frequency content than would have been measured at the magnet bore. Hence, our noise spectra may not fully depict the noise as experienced by the participant in the magnet. In any case, the shift in frequency content of the MR scanner noise is in agreement with the shift in the frequency response of the behavioral and fMRI measurements, demonstrating the direct effect of scanner noise frequency on studies of audition. Other researchers including Talavage et al. [2000] have also suggested that fMRI studies of the auditory cortex may require the use of spectrally separate frequencies, avoiding in particular the dominant frequency of the particular scanner noise. In this study, Protocol 2 always followed Protocol 1. It is possible that our results may be influenced by this order. However, the effects observed were auditory frequency-specific and, therefore, not likely due to other effects such as fatigue. Our data also did not exhibit any adaptation effects.

Psychophysical Results

Testing was not conducted in the absence of noise since there was always background noise present in the magnet room, such as the “chirping” of the cooling pumps, which may have had an interfering effect on behavioral measurements. The significant difference in the behavioral response (i.e., the perception of loudness) between Protocol 1 and Protocol 2 at 2,000 Hz (as well as a trend at 1,000 Hz) was likely attributable to MR scanner noise, since the MR scanner noise also shifted from ~1,000 to 2,000 Hz from Protocol 1 to Protocol 2.

Participants demonstrated a significant bias towards choosing higher frequencies as louder than lower frequencies even though the tones were approximately equal in loudness at a sound level of ~85 dB SPL, sufficient to overcome the frequency sensitivity commonly measured near hearing threshold levels. The ability for humans to perceive different sound frequencies is influenced by the characteristics of the auditory system. This enhances our ability to perceive sounds in the range between 3–4 kHz for speech perception [Zwicker and Fastl, 1999], and may explain the natural bias towards these frequencies.

fMRI Results

The “amount of fMRI activity” and the proportion of tonotopic voxels were significantly different between Protocol 1 and Protocol 2, in agreement with the behavioral data. The decrease in the amount of activity near scanner noise frequencies may be the result of an inflated baseline of activity [Bandettini et al. 1998]. In addition, there was a bias in the fMRI data of increased activation at the lower frequencies. This increased low-frequency fMRI activity may be a consequence of partial voluming due to abutting of core and belt low-frequency auditory areas [Formisano et al., 2003] or the amount of acoustic energy that travels through the auditory system with low frequencies [Rhode, 1980; Robles and Ruggero, 2001].

Tonotopic Mapping

Several patterns within the tonotopic maps agree with hypothesized tonotopy [Bertrand et al., 1991; Bilecen et al., 1998b; Elberling et al., 1982; Formisano et al., 2003; Lauter et al., 1985; Lockwood et al., 1999; Pantev et al., 1995, 1998; Strainer et al., 1997; Tiitinen et al., 1993; Wessinger et al., 1997; Yamamoto et al., 1988, 1992]. High frequencies, shown in green and blue in Figure 4, tended to be medial, and lower frequencies, shown in red and yellow (Fig. 4), tended to be lateral (subject GJ in Fig. 4A and subject CT in Fig. 4B). However, the opposite pattern was found in other individuals and slices (subject KS in Fig. 4C and the right hemisphere of subject MC in Fig. 4A). In some cases, multiple maps were obtained that interestingly show a high-to-low next to a low-to-high orientation (left hemisphere of GJ in Fig. 4A and left hemisphere of CT in Fig. 4B) as recently shown [Formisano et al., 2003]. Our results showed that reasonable tonotopy is achievable if responses to scanner noise frequencies are not considered.

CONCLUSIONS

The goal of the current study was to demonstrate quantitatively how MR scanner noise of known frequency content influences auditory cortex activity in a frequency-specific manner. These findings may help to explain the conflicting results found in the literature with regards to tonotopic organization. Our findings indicate a reduced behavioral and cortical response to tones near scanner frequencies. Therefore, tones used in tonotopic map estimation of the auditory cortex should avoid the scanner noise frequencies as much as possible. Using sparse imaging techniques may help to overcome scanner noise issues, however these paradigms involve greatly increased study times and introduce consequent subject comfort issues. The upward spread of masking also poses challenges as low-frequency stimuli may activate higher frequency areas to some degree. One possible solution may be to increase the spatial resolution of the imaging technique to determine how centers of mass of activation move across the cortex as tonal frequencies are increased.

Cortical flattening may help to visualize the topography more clearly [Formisano et al., 2003].

Interestingly, the behavioral and fMRI data showed opposite biases. The behavioral data were biased towards high frequencies and the fMRI results were biased towards low frequencies, suggesting that researchers should be cautious of using high-intensity auditory stimuli when investigating correlations between behavior and fMRI. Nonetheless, both measures detected a difference in response near scanner noise frequencies when the imaging protocol was changed, demonstrating a significant effect of scanner noise on auditory cortical activation. Our results demonstrate the difficulties associated with fMRI studies of audition, and may help researchers in experimental design of future investigations.

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