NeuroImage 49 (2010) 3027–3038

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Modeling hemodynamic responses in auditory cortex at 1.5 T using variable duration imaging acoustic noise

Shuowen Hu [a,b,*], Olumide Olulade [a], Javier Gonzalez Castillo [c], Joseph Santos [c], Sungeun Kim [a], Gregory G. Tamer Jr. [c], Wen-Ming Luh [d], Thomas M. Talavage [a,c]

[a] School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA
[b] Army Research Laboratory, Adelphi, MD, USA
[c] Weldon School of Biomedical Engineering, Purdue University, West Lafayette, IN, USA
[d] National Institute of Mental Health, National Institutes of Health, Bethesda, MD, USA

ARTICLE INFO

Article history:
Received 18 September 2009
Revised 10 November 2009
Accepted 19 November 2009
Available online 4 December 2009

Keywords:
Imaging acoustic noise
Functional MRI
Hemodynamic response
Linear systems

ABSTRACT

A confound for functional magnetic resonance imaging (fMRI), especially for auditory studies, is the presence of imaging acoustic noise generated mainly as a byproduct of rapid gradient switching during volume acquisition and, to a lesser extent, the radiofrequency transmit. This work utilized a novel pulse sequence to present actual imaging acoustic noise for characterization of the induced hemodynamic responses and assessment of linearity in the primary auditory cortex with respect to noise duration. Results show that responses to brief duration (46 ms) imaging acoustic noise is highly nonlinear while responses to longer duration (>1 s) imaging acoustic noise becomes approximately linear, with the right primary auditory cortex exhibiting a higher degree of nonlinearity than the left for the investigated noise durations. This study also assessed the spatial extent of activation induced by imaging acoustic noise, showing that the use of modeled responses (specific to imaging acoustic noise) as the reference waveform revealed additional activations in the auditory cortex not observed with a canonical gamma variate reference waveform, suggesting an improvement in detection sensitivity for imaging acoustic noise-induced activity. Longer duration (1.5 s) imaging acoustic noise was observed to induce activity that expanded outwards from Heschl's gyrus to cover the superior temporal gyrus as well as parts of the middle temporal gyrus and insula, potentially affecting higher level acoustic processing.

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Introduction

The presence of acoustic noise in functional magnetic resonance imaging (fMRI) is a confounding factor that has long been a concern for the experimental community, especially for those conducting fMRI studies requiring accurate perception of complex auditory stimuli. This acoustic noise (hereafter referred to as imaging acoustic noise) is a byproduct of the echo planar imaging acquisition technique typically employed for fMRI, sometimes achieving intensity levels at or above 110 decibels sound pressure level (dB SPL) (Ravicz et al., 2000). Imaging acoustic noise not only alters the sensory perception of the desired auditory stimuli (Hall et al., 2009), but also has been shown to produce blood oxygenation level-dependent (BOLD) responses in the auditory cortex potentially interfering with responses to desired auditory stimuli (Bandettini et al., 1998; Talavage et al., 1999; Novitski et al., 2001; Moelker and Pattynama, 2003; Talavage and Edmister, 2004).

Characterization of the hemodynamic response induced by imaging acoustic noise and subsequent assessment of linearity is crucial for the development of effective compensation methods that may account for the effects of imaging acoustic noise in auditory fMRI. Tamer et al. (2009) observed that the hemodynamic response induced by an "elemental unit" of imaging acoustic noise (i.e., from acquisition of a single slice) is concomitant in amplitude to that induced by a typical acoustic stimulus. For a brief duration acoustic stimulus, such as an elemental unit of imaging acoustic noise, the hemodynamic response is expected to be highly nonlinear. Soltysik et al. (2004) observed nonlinearity in the primary auditory cortex to trains of 125 ms pure tone bursts (spaced 125 ms apart) lasting up to 10 s in duration, but for longer duration stimuli, responses became approximately linear. Similarly, Robson et al. (1998) observed nonlinear behavior in the primary auditory cortex to trains of 100 ms tone bursts (spaced 100 ms apart) lasting less than 6 s in duration. As imaging acoustic noise consists of brief 46 ms bursts of spectrally complex "pings," the induced hemodynamic responses can be expected to differ somewhat from the responses obtained in the aforementioned studies, although the general trend is expected to be similar.

Mitigation of the effects of imaging acoustic noise has been previously sought through modifications of scanner hardware (Ravicz et al., 2000; Edelstein et al., 2002; Edelstein et al., 2005) and through the addition of passive attenuation measures in the experimental

* Corresponding author. 465 Northwestern Avenue, West Lafayette, IN 47906, USA.
E-mail address: hu@ecn.purdue.edu (S. Hu).

1053-8119/$ – see front matter. Published by Elsevier Inc.
doi:10.1016/j.neuroimage.2009.11.051

setup (Ravicz et al., 2000), the simplest of which involves the use of earmuff and/or eartips to achieve passive attenuation of up to approximately 45 dB. Though passive attenuation reduces the intensity of imaging acoustic noise, the subsisting imaging acoustic noise remains clearly audible to the subject. This subsisting imaging acoustic noise is transmitted by both air conduction, via the ear canal, and bone conduction, via the direct contact between skeletal (including cranial) bones and the vibrating coil base and patient bed assembly (Ravicz and Melcher, 2001). Alleviation of the effects of imaging acoustic noise has also been sought through experimental efforts such as the usage of clustered volume acquisition (Edmister et al., 1999) to allow presentation of auditory stimuli in the quiescent period between volume acquisitions, mitigating masking of the desired stimuli by imaging acoustic noise. Clustered volume acquisitions are commonly employed with a longer repetition time to further reduce the interaction between noise- and stimulus-induced responses, but come at the cost of decreased statistical power, necessitating either recruitment of a larger subject pool or longer experiments. While successful in achieving their primary goals, these efforts cannot achieve optimality (i.e., no noise perception), and the noise remains a critical consideration in auditory fMRI.

Characterization of the BOLD response to imaging acoustic noise and subsequent modeling of the interaction between the response to this noise and the response to the desired stimuli may be the best procedure for improving auditory fMRI experiments. Previous studies utilized recorded scanner background noise (Gaab et al., 2007; Hall et al., 2000a,b), which does not take into account physical stimulation through bone conduction and vibration of the patient bed assembly (Ravicz and Melcher, 2001; Hiltunen et al., 2006; Tomasi et al., 2004). This work utilizes radiofrequency disabled volume gradient sequences in between actual clustered volume acquisitions (Edmister et al., 1999) to generate real imaging acoustic noise without perturbing longitudinal magnetization. The objectives of this work were to assess the linearity of the responses induced by imaging acoustic noise and to examine the changes in the spatial extent of brain activation with respect to the duration/quantity of imaging acoustic noise. Assessment of the linearity of imaging acoustic noise-induced responses will enable prediction of distortions to the shape of the desired response while characterization of the extent of spatial activation arising from imaging acoustic noise will enable prior identification of those areas most likely to be negatively affected by the presence of imaging acoustic noise. In addition, knowledge gained from these efforts will likely provide further insight into cortical behavior and function.

Materials and methods

Paradigm

Radiofrequency (RF) disabled volume gradient sequences, henceforth referred to as dummy volumes, were applied at variable post-offset sample times between actual volume acquisitions. These dummy volumes were generated using a normal blipped EPI slice acquisition with a zero-amplitude RF pulse, generating imaging acoustic noise (i.e., a “ping” sound for each slice of the dummy volume) without perturbing longitudinal magnetization. The imaging acoustic noise intensity on the General Electric 1.5 T Signa CVi used in this study is approximately 97 dB SPL.

Three experiments were conducted, in each of which a dummy volume, comprising a 1-, 10-, or 15-slice RF-disabled gradient sequence, was effected to generate 1-, 10-, and 15-ping imaging acoustic noise, respectively. The gradient sequence was grouped as per a clustered volume acquisition (CVA) (Edmister et al., 1999) and generated in the quiescent period between actual CVAs, occurring at a fixed TR. The 1-slice RF-disabled gradient sequence generated a single ping imaging acoustic noise 46 ms in duration that occurs approximately 20 ms into a 100 ms duration pulse sequence. Note that all analysis in this work is performed with respect to the onset of the pulse sequence. The 10-ping (1 s overall duration) and 15-ping (1.5 s overall duration) stimuli consist of trains of perceptually distinct 46 ms pings occurring at a rate of approximately 10 per second. The generated ping stimuli are spectrally diverse, containing many distinct peaks in the audible frequency range (Tamer et al., 2009). For all three cases, the delay between a dummy volume and the subsequent actual volume acquisition was varied over a set of post-offset (relative to the dummy volume) sampling times (Table 1) using a stroboscopic paradigm (Belin et al., 1999), including a null condition in which no dummy volume was generated. Variation of the temporal position of the dummy volume between actual image acquisitions enables the measurement of the hemodynamic response induced by pure imaging acoustic noise produced by the dummy volume, as depicted in Fig. 1. Twelve trials of each post-offset sample time and the null condition were acquired for each experiment. The long TR values (26 s for 1-ping; 33 s for 10- and 15-ping experiments) were used to permit the hemodynamic response induced by the previous volume acquisition to approach baseline before the presentation of the dummy volume.

During the scanning session, subjects wore earmuffs with custom eartips, achieving overall attenuation of approximately 42 dB. The eartips were connected to a pneumatic sound delivery system via inserted plastic tubing to mimic the setup of a typical auditory fMRI experiment, but no acoustic stimulus was delivered through the pneumatic system. During the functional runs, subjects viewed a self-chosen movie that was projected onto a screen and viewed through a mirror without subtitles or sound. The use of a subject-selected movie (typically chosen to be an action movie with minimal dialog) served to maintain subject interest in and attention to the presented visual stimulus, enabling the assessment of brain response to the imaging acoustic noise as the subjects listened in a passive manner, mimicking a typical experiment in which the imaging acoustic noise is not the intended target of attention.

Subjects

Forty adult subjects (20 males, 20 females) were imaged on a General Electric 1.5 T Signa CVi (InnerVision Advanced Medical Imaging; Lafayette, IN). All subjects reported normal hearing with no history of hearing impairment, and gave written informed consent before participation in the study. A group of 20 subjects underwent one scanning session in which a 15-ping train was used as the auditory stimulus, and a second group of 20 subjects participated in a single session in which responses to trains of 1- and 10-ping imaging acoustic noise were measured. All subjects were instructed to lie still and watch the movie during the functional runs.

Imaging protocol

Each imaging session consisted of four data acquisition segments: (1) a high-resolution anatomical reference data set using a standard birdcage head coil (124 slices; in-plane resolution = 0.9375 mm × 0.9375 mm), (2) a sagittal localizer to identify desired imaging volume, (3) high-

Table 1
Post-offset sample times for 1-, 10-, and 15-slice dummy volume experiments. Note that times are measured relative to the offset of the dummy volume.

Dummy Volume	TR (s)	No. sample times	Variable post-offset sample times (s)
1-slice	29	9	1.5, 3, 3.5, 4, 5, 6.5, 7.5, 8.5, 12.5
10-slice	33	7	2, 2.5, 3, 4, 5.5, 7.5, 11.5
15-slice	33	14	1.5, 2, 2.5, 3, 3.5, 4, 5, 7, 9, 10, 11, 12.5, 14, 15

A null condition was also acquired in which no dummy volume was presented.