Auditory fMRI of Sound Intensity and Loudness for Unilateral Stimulation

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Introduction

Loudness is mainly the perceptual correlate of sound intensity, but is also affected by other sound parameters like e.g. duration, spectral content and temporal modulation as well as several more acoustic and non-acoustic factors. The physiological correlate of loudness perception in the human central auditory pathway is not yet completely understood [1]. Some auditory functional magnetic resonance imaging (fMRI) studies indicate that neural activation, at least in auditory cortex (AC), might be more a representation of perceived loudness rather than of physical sound pressure level [2,3,4]. The current literature still does not provide definite answers to the following questions: (1) At what stage or stages along the auditory pathway is sound intensity transformed into its perceptual correlate (i.e. loudness)? (2) What are the functional differences across regions within AC with respect to loudness-related activation?

The present study therefore aimed at extending the current literature by providing a more distinguished characterization of the neural representation of sound intensity and loudness. In a group of normal hearing listeners, we systematically explored the interrelation of ear of entry, sound pressure level, individual loudness and brain activation, as defined by the blood oxygenation level dependent (BOLD) signal, in the ascending auditory pathway and within AC.

Methods

Participants

Thirteen normal-hearing volunteers (aged 34 ± 8 years, 4 females) participated in this study. Each participant attended two experimental sessions. In the first session, standard audiometry and an adaptive categorical loudness scaling procedure [5] were performed in a sound booth. In the second session, auditory fMRI was performed while subjects were doing a simple listening task in the MR scanner.

Stimuli

All stimuli consisted of 1/3 octave band-pass low-noise noise [6] bursts at 4 kHz center frequency and were delivered via MR compatible insert earphones. In the loudness scaling procedure, single noise bursts with a maximum intensity of 105 dB SPL were used under left monaural, right monaural and diotic stimulus conditions. In the MRI experiment, trains of noise bursts with a total duration of 4.75 s were presented left and right monaurally at 37, 52, 67, 82 and 97 dB SPL and diotically at 82 dB SPL.

MRI data acquisition

Functional and structural images were acquired on a 3-T MRI system (Siemens MAGNETOM Verio). Functional images were obtained using T2*-weighted gradient echo planar imaging (EPI), with a sparse sampling paradigm to reduce the influence of the acoustic scanner noise [7]. Stimuli were presented in pseudorandomized order during 5-s gaps of scanner silence in between two successive volume acquisitions. Each of the eleven stimulus conditions plus a silence condition, which served as baseline, was presented 36 times over the course of the experiment. For the purpose of maintaining the participants' attention towards the acoustic stimuli, they were asked to count the number of occasionally presented deviants, characterized by a transient dip in sound level in one of the noise bursts.

Psychoacoustic evaluation

Individual loudness judgments obtained in the scaling procedure were used to fit loudness functions for each participant by means of a recently suggested fitting method [8]. Loudness estimates for the stimulus conditions used in the MRI experiment were extracted from the individual loudness functions and were used for further analyses.

MRI data analysis

Standard preprocessing of the imaging data (including spatial smoothing with a 5-mm FWHM Gaussian kernel) and general linear model (GLM) estimation was done using SPM8 [9]. Different GLMs were set up to model the BOLD signal in every voxel as a function of ear of entry and either sound pressure level or loudness estimates for each participant. Based on the resulting (1st level) coefficient maps, two approaches were carried out to analyze the relationship between neural activation and sound intensity or loudness for left or right stimuli across subjects (at the 2nd level):

(1) A functional activation map trend analysis to detect voxels in the brain characterized by a significant linear or quadratic trend (over and above the linear trend) of signal change with sound intensity or loudness for left or right ear stimulation.

(2) A region-of-interest analysis. For each participant, twelve auditory ROIs were defined based on anatomical landmarks in the individual structural images: Left and right inferior colliculus (IC), medial geniculate body (MGB), Planum temporale (PT), posterior medial (HGpm), central (HGc) and anterolateral (HGal) parts of the first Heschl's gyrus. The average signal changes from baseline of all voxels within 5-mm spheres centered at individual ROI coordinates were then entered into random slope linear mixed effects models (LMMs). For each of the twelve ROIs, eight separate models (2 x 2 x 2) were estimated modeling the ROI percent signal change as a linear or quadratic function of sound intensity or individual loudness for left and right ear of entry. Model parameters were estimated by means of maximum-likelihood. Likelihood-ratio tests were conducted to assess significance of the models. To provide

measures of the models' goodness-of-fits in terms of explanatory power, marginal R^2 statistics (R^2_m), representing the partition of variance in the model explained by the fixed (population) effects, were calculated according to [10].

Results

Figure 1 illustrates the results of the categorical loudness scaling procedure for the group of 13 participants. Group averaged fitted loudness curves [8] for left monaural, right monaural and binaural stimuli are shown, along with the interindividual standard deviations of loudness estimates for the stimulus intensities presented in the MRI experiment. All three curves are characterized by a nearly linear growth of categorical loudness with sound intensity between 20 and 80 dB SPL and an increase in the steepness of the slope around 90 dB SPL. There was virtually no difference in perceived loudness between left and right ear of entry. For diotic stimulation, the expected 3 dB effect of binaural loudness summation is clearly visible.

In Figure 2, the results from the region-of-interest analysis are illustrated. Marginal R^2 statistics [10], representing the partition of variance in the models explained by (i.e. the explanatory power of) the fixed (population) effects, displayed a largely symmetrical pattern across hemispheres. The highest values were found in the posterior medial parts of Heschl's Gyri, whereas the subcortical ROIs and left HGal were characterized by the lowest R^2_m values. Contralateral stimuli generally yielded better fits, albeit with varying degree of lateralization across ROIs. Linear fits with loudness, although being outmatched by quadratic fits with sound intensity in the majority of cortical ROIs, still showed slightly better goodness-of-fits as compared to linear sound intensity models throughout all investigated regions. Quadratic fits with loudness are not shown, since only 4 out of 24 models reached significance according to LLR tests.

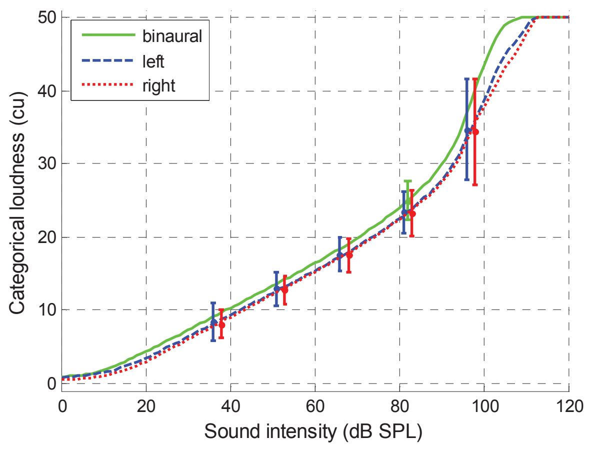

Figure 1: Categorical loudness as a function of sound intensity and ear of entry. The three curves represent group averages of individual loudness fits. Error bars represent interindividual standard deviations of loudness estimates for the stimulus intensities presented in the MRI experiment.

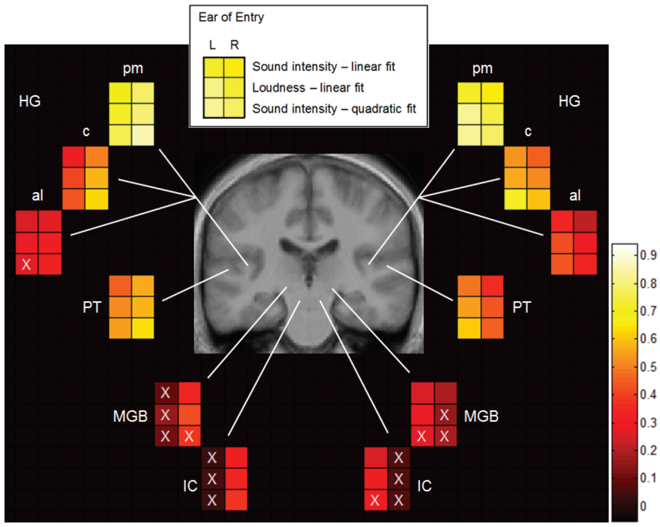

Figure 2: Region-of-interest (ROI) analysis. Marginal R^2 statistics, representing the partition of variance explained by fixed effects, of linear and quadratic model fits with sound intensity as well as linear fits with loudness for left (L) and right (R) monaural stimuli corresponding to each auditory ROI. Non-significant models are marked with a white "X". Quadratic fits with loudness are not shown, since only 4 out of 24 models reached significance.

Figure 3 illustrates the results of the functional activation map trend analysis probing linear and quadratic growths of activation with sound intensity and loudness for left and right ear of entry. Second-level t-statistic parametric maps are thresholded at a significance level of $p < 0.001$ (uncorrected) and are overlaid onto the group average structural image at four axial slices corresponding roughly to the average ROI coordinates defined for all participants. The activation patterns for the linear intensity and loudness contrasts appear highly similar, whereas they differed considerably between the quadratic contrasts: While large clusters of voxels in AC and smaller ones in IC and MGB were characterized by a significant quadratic signal growth with sound intensity over and above the linear trend, only very few voxels displayed a quadratic relationship with categorical loudness.

Summary

- Throughout all investigated stages of the auditory system, except for ipsilateral stimuli in IC and MGB, neural activation as reflected by the fMRI BOLD response was significantly related to physical sound intensity as well as individual loudness estimates.
- The relationship between activation magnitude and sound intensity or loudness was most prominent and consistent in primary auditory cortex (particularly posterior medial section of Heschl's Gyrus), a little less so in Planum temporale and comparatively weak in the anterolateral section of HG and subcortical regions, which largely is in line with the existing literature [e.g. 11,12].

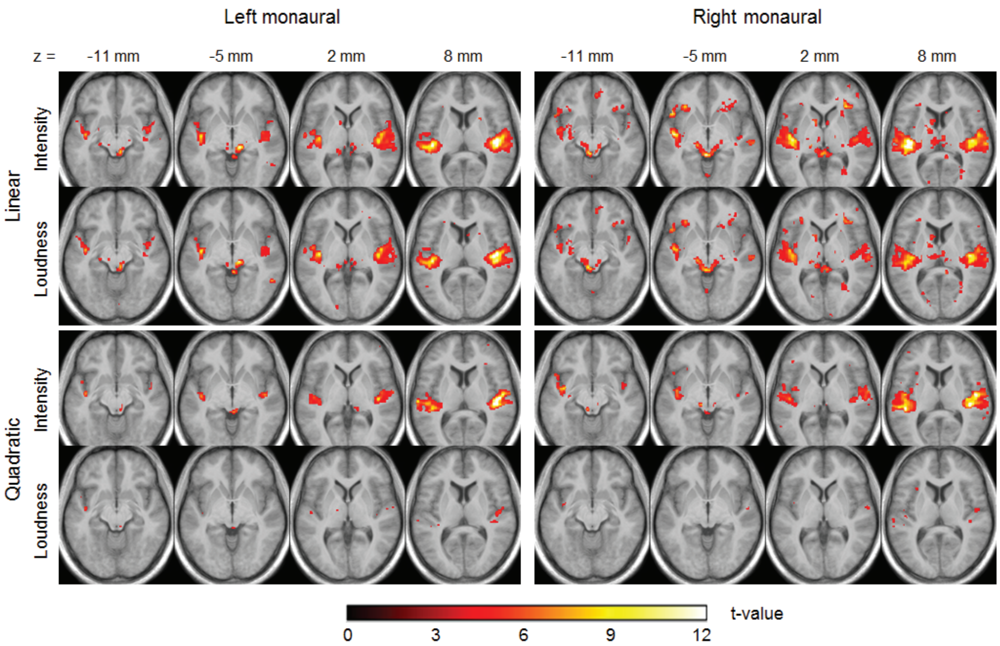

Figure 3: Trend analysis of brain activation as a linear and quadratic function of sound intensity and categorical loudness for left and right monaural stimuli. Second-level t-statistic maps are thresholded at a significance level of $p < 0.001$ ($t > 3.93$) and overlaid onto the group average structural image at four axial slices corresponding roughly to the group average z-coordinates of the auditory ROIs: z = -11 mm→ IC; z = -5 mm→ MGB; z = 2 mm→ HGc/HGal; z = 8 mm→ HGpm/PT.

- Activity at all stages of the auditory pathway appeared to be more closely related to changes in sound level or perceived loudness for stimuli presented at the contralateral ear. However, the degree of lateralization was considerably different for the different regions.
- While changes in sound intensity were reflected by a quadratic growth of neural activity, especially in cortical areas, the relation between activation and categorical loudness can be described as predominantly linear in all investigated regions-of-interest, which is in line with [3,4].

Conclusion

Our findings suggest that functional differentiation, both between cortical and subcortical regions (in support of [4]) as well as between regions of auditory cortex, is an important issue to consider in the pursuit of a complete and comprehensive understanding of the physiological correlates of loudness perception.

References

[1] Uppenkamp, S., Röhl, M.: Human auditory imaging of sound intensity and loudness. Hearing Research 307 (2014), 65-73

[2] Hall, D.A., Haggard, M.P., Summerfield, A.Q., Akeroyd, M.A., Palmer, A.R.: Functional magnetic resonance imaging of sound-level encoding in the absence of background scanner noise. The Journal of the Acoustical Society of America 109 (2001), 1559-1570

[3] Langers, D.R.M., van Dijk, P., Schoenmaker, E.S., Backes, W.H.: fMRI activation in relation to sound intensity and loudness. Neuroimage 35 (2007), 709-718

[4] Röhl, M., Uppenkamp, S.: Neural coding of sound intensity and loudness in the human auditory system. Journal of the Association for Research in Otolaryngology 13 (2012), 369-379

[5] Brand, T., Hohmann, V.: An adaptive procedure for categorical loudness scaling. The Journal of the Acoustical Society of America 112 (2002), 1597–1604

[6] Pumplin, J.: Low-noise noise. The Journal of the Acoustical Society of America 78 (1985), 100-104

[7] Hall, D.A., Summerfield, A.Q., Goncalves, M.S., Foster, J.R., Palmer, A.R., Bowtell, R.W.: “Sparse” temporal sampling in auditory fMRI. Human Brain Mapping 7 (1999), 213-223

[8] Oetting, D., Brand, T., Ewert, S.D.: Optimized loudness-function estimation for categorical loudness scaling data. Hearing Research 316 (2014), 16-27

[9] SPM, URL: `http://www.fil.ion.ucl.ac.uk/spm/`

[10] Johnson, P.C.D.: Extension of Nakagawa & Schielzeth’s R^2_{GLMM} to random slope models. Methods in Ecology and Evolution 5 (2014), 944-946

[11] Brechmann, A., Baumgart, F., Scheich, H.: Sound level-dependent representation of frequency modulations in human auditory cortex: A low-noise fMRI study. Journal of Neurophysiology 87 (2002), 423-433

[12] Ernst, S.M.A., Verhey, J.L., Uppenkamp, S.: Spatial dissociation of changes of level and signal-to-noise ratio in auditory cortex for tones in noise. Neuroimage 43 (2008), 321-328