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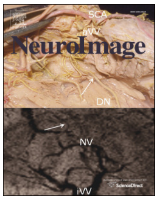

# Auditory intensity processing: Categorization versus comparison

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ABSTRACT

Intensity is an important parameter for the perception of complex auditory stimuli like speech. The results of previous studies on the processing of intensity are diverse since left-lateralized, right-lateralized and non-lateralized processing was suggested. A clear dependence of the lateralization on the kind of stimuli and/or task is not apparent. With the present functional magnetic resonance imaging (fMRI) study, we directly investigated the differences between a categorical and comparative task. To determine hemispheric involvement we used a method with contralateral noise presentation. Harmonic complexes were presented monaurally without and with contralateral noise. Both categorization and comparison of harmonic complexes according to their intensity more strongly involved the left than the right auditory cortex shown by a stronger effect of the additional noise on the activity in the left auditory cortex. Together with previous results, this suggests that left-lateralized processing of intensity in the auditory cortex can be observed independent of task and stimuli. The comparison task more strongly engaged the left auditory cortex than the categorization task probably due the additional need for sequential comparison and the right auditory cortex probably due to capacity reasons. Comparison also more strongly engaged areas associated with attentional processes and areas responsible for motor response selection. We suggest this to be caused by a more difficult response selection and by the need for continuous update of information in reference memory during the comparison task.

## Introduction

Intensity is a basic acoustic parameter for the perception of complex acoustic stimuli like speech and music. Decisions about intensity are relative, i.e., the decision of whether a sound is soft or loud always requires a reference for comparison. Previous studies on intensity discrimination produced equivocal results regarding the lateralization of brain activity. Right but not left temporal lobectomy resulted in an increased number of errors in a loudness discrimination task on pure tones (Milner, 1962). In accordance, the results of a positron emission tomography (PET) study (Belin et al., 1998) showed an engagement of two networks in the detection of intensity deviants in sequences of harmonic sounds, i.e., a right frontoparietal network for attentional processes and a region in the right posterior temporal gyrus for sensory computation of differences in sound intensity. Another psychoacoustic study also points to a stronger involvement of the right hemisphere in the discrimination of intensity of syllables and tone complexes in a dichotic stimulation design whereas during monaural presentation an ear advantage was not found (Brancucci et al., 2005). In contrast, a functional magnetic resonance imaging (fMRI) study on intensity discrimination revealed a leftward dominance of activity in the temporal lobe with tone complexes with formant-like spacing of the components (Reiterer et al., 2008). Similarly, categorization of frequency modulated (FM) tones based on their intensity seems to mainly engage the left auditory cortex (AC) shown by an fMRI experiment with contralateral noise presentation (Angenstein and Brechmann, 2013a). Yet another psychoacoustic study did not find any difference between left and right ear presentation during loudness discrimination on pure tones with 20 dB softer contralateral noise (Dykstra et al., 2012).

Potential explanations for these discrepancies may be differences in tasks, kind of stimuli (e.g., verbal vs. nonverbal, intensity differences, gaps) or measurement procedure. Firstly, some stimuli may produce a bias towards one hemisphere, e.g., speech to the left hemisphere or FM sweeps to the right AC (Behne et al., 2005; Brechmann and Scheich, 2005). However, Brancucci et al. (2005) used syllables but reported a stronger right hemispheric involvement in intensity processing with a dichotic listening experiment (note that results of dichotic experiments are less reliable with respect to the lateralization of processing than brain imaging results (Bethmann et al., 2007)). In addition, Angenstein and Brechmann (2013a) found a stronger left-hemispheric involvement in intensity processing with FM sweeps. Moreover, studies with tones found diverse results regarding hemispheric involvement (Belin et al., 1998; Dykstra et al., 2012; Milner, 1962; Reiterer et al., 2008). Thus, the kind of stimuli does not seem to be an important factor for biasing lateralization of intensity processing.

The second factor that potentially determines laterality is the task. In most of the studies mentioned above, the intensity had to be compared within pairs of sounds (Brancucci et al., 2005; Dykstra et al., 2012; Milner, 1962; Reiterer et al., 2008) and thus required sequential

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comparison between the actual and the previous tone. This means with each presented pair the reference for comparison had to be updated. Such sequential comparison can change the lateralization of activity towards the left AC even though the processing of the feature itself is lateralized to the right AC (Angenstein and Brechmann, 2013b; Brechmann et al., 2007). Whatsoever, the majority of studies on intensity discrimination employing such comparisons did not find a bias towards the left hemisphere (Brancucci et al., 2005; Dykstra et al., 2012; Milner, 1962; but see Reiterer et al., 2008).

Our previous study on intensity processing showed a left hemispheric involvement and employed a categorical decision. Thus, no sequential comparison and continuous updating of the reference tone were required. In the present fMRI study, we asked the question whether this difference in task type may contribute to differences in hemispheric involvement. To this end, we compared fMRI activation resulting from categorization versus sequential comparison of harmonic tone complexes based on their intensity. This approach precludes the effect of different stimuli on the results and prevents an influence of linguistic or other potentially biasing sound features on the lateralization of processing.

For the investigation, we used a method that is able to elucidate differential hemispheric contribution to the processing, based on an increase in activity by presenting additional noise contralateral to ipsilateral presented task-relevant stimuli (Angenstein and Brechmann, 2013a, b; Behne et al., 2005; Behne et al., 2006; Stefanatos et al., 2008). The task-relevant stimuli are presented monaurally with and without contralateral noise. The method makes use of the fact that the input from the contralateral ear dominates in the AC and suppresses the input from the ipsilateral ear (Brancucci et al., 2004; Kaneko et al., 2003; Kimura, 1967). The additional contralateral noise leads to an increase in activity in the AC during ipsilateral presentation of the task-relevant stimuli when the AC of this hemisphere is substantially involved in the processing of the task. We propose that this increase in activity is caused by compensatory mechanisms in order to enable an adequate task performance during this condition with reduced signal-to-noise ratio. Therefore, the location of this increase in activity reveals the location of task processing. This method offers two advantages: The location for the processing of a specific task can be determined by using one set of stimuli in combination with a single task, and a direct comparison of activity between hemispheres is not required.

For the categorization of tones based on their intensity we expected a stronger involvement of the left AC. We derived this hypothesis from the previous study in which FM tones had to be categorized based on their intensity (Angenstein and Brechmann, 2013a). With respect to the comparison of tones based on their intensity no specific hypothesis can be formulated due to the equivocal results of the previous studies employing comparison of intensity within pairs of sounds (Dykstra et al., 2012; Milner, 1962; Reiterer et al., 2008). However, our own results on sequential comparisons of other features of sounds would suggest a bias towards the left AC (Angenstein and Brechmann, 2013b; Brechmann et al., 2007).

## Materials and methods

*Participants.* Eighteen right-handed volunteers (Edinburgh Handedness Inventory; laterality quotient ≥ +60) participated in the present study, with normal hearing (hearing level ≤ 15 dB from 125 Hz to 6 kHz, interaural difference at each tested frequency ≤ 10 dB) and left-lateralized speech processing tested by an fMRI paradigm (Bethmann et al., 2007). Participants (age 21–38 years, mean age 26 years, 10 females) gave written informed consent to the study, which was approved by the ethics committee of the University of Magdeburg. Eleven additional participants were excluded from the analysis because their performance was below 70% for each stimulus category (3 cases), their head movements during the fMRI-measurement were stronger than 2 mm translation and/or 2° rotation or more than 0.6 mm translation from one volume to the next (5 cases) or because of technical problems during stimulus presentation and response recording (3 cases).

*Stimuli and tasks.* Harmonic tone complexes served as acoustic stimuli. They lasted 400 (i.e., short) or 600 ms (i.e., long) including a linear rise/fall time of 10 ms. The tone complexes consisted of five harmonics of decreasing amplitude (100% amplitude for the fundamental frequency, 80% for 2nd harmonic, 60% for 3rd, 40% for 4th, 20% for 5th). The frequencies of the fundamentals (F0) were 200 Hz, 240 Hz, 280 Hz … 760 Hz. We applied some adaptation of the stimulus intensities depending on the frequency content of the stimuli to achieve comparable loudness between sounds of different pitch (see Inline Supplementary Figure S1). For this, the root mean square (RMS) amplitude of the sounds was adjusted in steps of 0.2 dB such that the sound with the highest pitch (F0 of 760 Hz) was 2.8 dB softer than the amplitude of the sound with the lowest pitch (F0 of 200 Hz). Thus, any remaining difference in perceived loudness of the individual sounds was well below the task relevant differences in loudness.

Inline Supplementary Fig. S1 can be found online at http://dx.doi.org/10.1016/j.neuroimage.2015.06.074.

From this set, sounds were randomly selected and presented in pairs with a gap of 50 ms. The pitch and the duration of the tones within a pair could differ. Regarding the task relevant loudness, we created the following conditions. (A) In the categorization task, the two sounds within a pair were both either soft or loud while these two loudness categories differed by 7 dB RMS amplitude. (B) In the comparison task, four different loudness categories differed by 6.5 dB RMS amplitude or 7 dB between the two softest categories. The two sounds within a pair always belonged to different loudness categories. (Note that a given sound from the two middle loudness categories could both serve as the loud and the soft sound within a pair.) The mean amplitude (RMS) of all stimuli was the same for the categorization and comparison condition.

During a single session, the tones were presented in 25 stimulation blocks of 21 s each, which alternated with 26 blocks of 19 s silence. Within each block of stimulation, 12 pairs of tones were presented with 750 ms of silence between the pairs. Each stimulation block included 12 short tones and 12 long tones. In the categorization condition, each stimulation block consisted of six soft pairs and six loud pairs. In the comparison condition, each stimulation block consisted of six pairs with the louder tone at the first position and six pairs with the louder tone at the second position. The tones within each block were presented either binaurally or monaurally to the right or left ear with or without continuous contralateral white noise. The amplitude (RMS) of the noise was 2 dB higher than the averaged amplitude of all tones. The amplitude of the binaurally presented tones was 4 dB lower than the amplitude of the monaurally presented tones in order to achieve a similar loudness percept. Five blocks for each of the five conditions (left tones without noise, left tones with noise, right tones without noise, right tones with noise and binaural tones) were presented in pseudo-randomized order such that two consecutive blocks never belonged to the same condition.

The same stimuli were first presented in a psychoacoustic session and then on another day in an fMRI session. The aim of the psychoacoustic session was to familiarize the participants with the tasks in order to get a stable performance in the fMRI session. In each session the participants had to solve two different tasks. In the categorization condition, they had to categorize the pairs based on their intensity (soft vs. loud). The participants had to press a button with their right index finger for a loud pair and another button with their right middle finger for a soft pair. In the comparison condition, they had to decide whether the first or second tone within a pair was louder than the other one. The participants had to press a button with their right index finger when the first tone was the louder one and another button with their right middle finger when the second tone was louder. The order of both tasks was balanced across participants.

For stimulus presentation and recording of behavioral responses, the Presentation software package (Neurobehavioral Systems, Albany, USA)