# Neuromagnetic measurement of sound location processing in the human brain

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## 1 Introduction

In their natural auditory environment, humans are faced with a highly complex array of stimulus sources of varying location, frequency, and intensity, usually overlapping in time. This three-dimensional auditory space is to be analysed and represented by the human brain for the organism to function adequately. Slightly simplifying, the human auditory cortex can be described as a two-dimensional array consisting of topographic representations for stimulus frequency and intensity. The question then arises how the human brain achieves the compression of the three-dimensional auditory space onto a two-dimensional plane. At present, very little is known about this feature of the human brain.

Non-invasive measurements utilizing electro- (EEG) and magnetoencephalography (MEG) have recently been used to study how stimulus features are represented in the human brain. Previous research has revealed how tone frequency and intensity are encoded in tonotopic [1-3] and amplitopic maps [4], respectively. Invasive animal studies further suggest that auditory cortex is able to represent various dynamic features, such as stimulus periodicity [5] and duration [6].

In addition to their spectral and temporal structure, natural sounds are perceived as having a location in auditory space. Behavioural studies indicate that sound localization in humans is based on the processing of binaural cues from interaural time and level differences (ITD and ILD, respectively) and monaural spectral cues from the filtering effects of the pinna, head and body [7]. The physiological basis of auditory space perception has mainly been studied invasively in animal models. These studies have revealed that the mammalian brain maps three-dimensional sound locations [8] with neurons in auditory cortex exhibiting tuning for stimulus location in auditory space [9]. While the processing of spatial sound in the human brain has remained largely unexplored, event-related potential (ERPs) and magnetic field (EMFs) measurements of, for example, the N1(m) [10] might offer a useful tool for studying sound localization in the human cortex.

The study of auditory spatial processing in the human brain has relied on two stimulus delivery methods: the use of headphones coupled with ITDs [11] and ILDs [12] and the use of multiple loudspeakers [12-14]. Both stimulation methods have certain restrictions: stimuli delivered through headphones are experienced as lateralized between the ears inside the head, rather than being localized outside the head as in natural spatial auditory perception [7]. The use of loudspeakers introduces possibly contaminating variables such as room reverberation and in MEG, the use of loudspeakers is impossible because magnetic components can not be placed inside the magnetically shielded measurement room.

Recent developments in sound reproduction technology allow the delivery of natural spatial sound through headphones. These developments are based on head-related transfer functions (HRTFs), digital filters capable of reproducing the filtering effects of the pinna, head and body [15]. HRTFs allow one to generate stimuli whose perceived angle of direction can be adjusted as desired. Thus, HRTFs allow us, for the first time, to use MEG in studying how the human cortex performs sound localization.

Here we focus on the role of auditory cortex in the processing of sounds representing a natural spatial environment by analyzing the N1m responses evoked by spatial stimuli generated using HRTFs.

## 2 Methods

A total of ten volunteers (9 right-handed, 2 female, mean age 29 years) served as subjects with informed consent and the approval of the Ethical Committee of Helsinki University Central Hospital (HUCH). The stimuli for the auditory localization task were produced using HRTFs provided by the University of Wisconsin [15]. The stimuli consisted of eight HRTF-filtered noise sequences (bandwidth 11 kHz, stimulus duration 50 ms, onset-to-onset interstimulus interval 800 ms) corresponding to eight azimuthal directions (0, 45, 90, 135, 180, 225, 270, and 315 degrees) in the horizontal plane (see Fig. 1).

In the MEG experiment, the stimuli were played by randomizing their direction angle. Stimulus intensity was scaled by adjusting the sound sample from $0^{o}$ azimuth to 75 dB SPL. Binaural loudness of stimuli from all directions was equalised using a loudness model [16]. The EMFs elicited by auditory stimuli were recorded (passband 0.03-100 Hz, sampling rate 400 Hz) with a 122-channel magnetometer (Neuromag-122). The subject, sitting in a reclining chair, watched a silent movie and was instructed not to pay attention to the auditory stimuli.

Brain activity time locked to stimulus onset was averaged over a 500-ms post-stimulus period (baseline-corrected with respect to a 100-ms pre-stimulus period) and filtered with a passband of 1-30 Hz. Electrodes monitoring both horizontal (HEOG) and vertical (VEOG) eye movements were used in removing artifacts, defined as activity in excess of $\pm$150 µV. Over 100 instances of each stimulus type were presented to each subject.

Data from channel pairs above the temporal lobes with the largest N1m amplitude were analyzed separately for both hemispheres. The N1m amplitude was determined as a vector sum from these channel pairs. As MEG sensors pick up brain activity maximally directly above the source [17], the channel pair at the response maximum indicates the approximate location of the underlying source.

The subjects were also tested with a behavioural match-to-sample task. The eight stimuli were first played in a clockwise sequence with the direction angle of the first sound randomized. Then a test sample from a random direction was played three times after which the subject indicated the direction angle of this test sample by a button press. Hit rates were calculated for each angle.

## 3 Results

The stimulus set used in the present experiment approximated the horizontal auditory plane well, with the behavioural match-to-sample task indicating that the samples were localized correctly with 67% accuracy. The probability of correctly performed localization increased to 86% when errors within the so called cones of confusion [7] (i.e. between direction angles $0^{o}$ & $180^{o}$, $45^{o}$ & $135^{o}$, $225^{o}$ & $315^{o}$) were ignored. These cones are regions in auditory space within which behavioural discrimination of the direction between sound sources is weak due to ITD and ILD varying only slightly because of the asymmetry of the head.

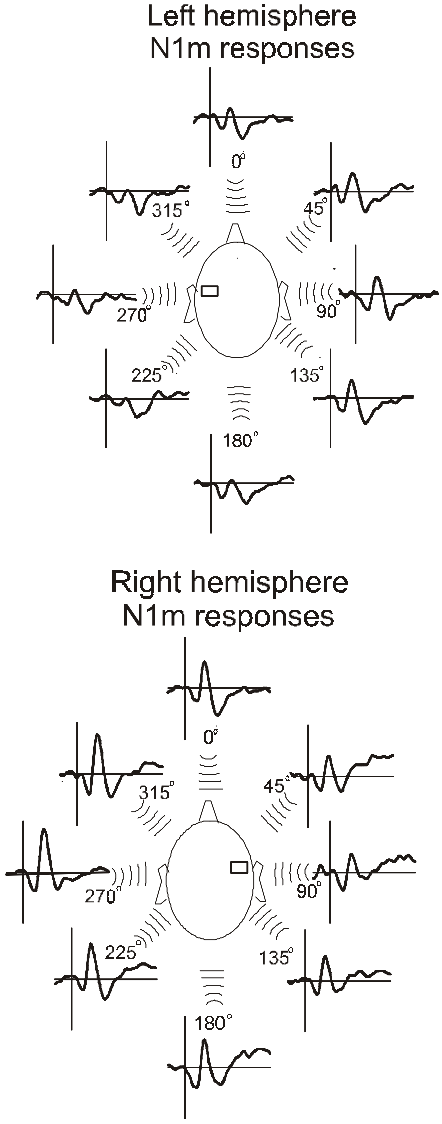


Figure 1: *Grand-averaged N1m responses of both hemispheres from the sensor maximally detecting N1m activity shown for each of the eight direction angles (time scale –100 – 500 ms; amplitude scale +40 fT/cm).*

All eight stimuli elicited prominent N1m responses, as can be seen in the grand-averaged responses of Figure 1. Both hemispheres exhibited tuning to the direction angle, with a contralateral maximum (direction angles $90^{o}$ and $270^{o}$, for the left and right hemisphere, respectively) and an ipsilateral minimum (direction angles $270^{o}$ and $90^{o}$ for the left and right hemisphere, respectively) in the amplitude of the N1m. The amplitude variation as a function of azimuthal degree was statistically significant over both the left ($F[1,7] = 3.09$, $p < 0.01$) and the right ($F[1,7] = 7.74$, $p < 0.001$) hemisphere.

Figure 2 shows the grand-averaged N1m amplitude over the eight stimulation conditions. The results indicate a right-hemispheric preponderance in the processing of the HRTF-filtered noise stimuli: The N1m responses were considerably larger in amplitude over the right than over the left hemisphere. The mean N1m amplitude across the eight direction angles was 39.1 fT/cm in the right and 24.5 fT/cm in the left hemisphere ($F[1,9] = 17.76$, $p < 0.01$). Further, the N1m amplitude variation (i.e., the difference between the maximum and minimum across azimuthal angle) was larger in the right (28.6 fT/cm) than in the left (14.8 fT/cm) hemisphere.

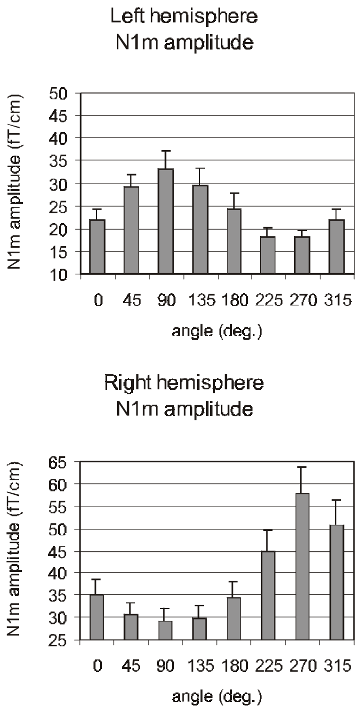


Figure 2: *The grand-averaged N1m amplitude behaviour calculated as the vector sum from the channel pair maximally detecting N1m activity over the left and right hemisphere (error bars indicate standard error of the mean).*

## 4 Discussion

The present results demonstrate that it is possible to extend non-invasive MEG research to studies of cortical processes in complex auditory environments by using HRTF-based stimuli. Our results show that both cortical hemispheres are sensitive to the location of sound in three-dimensional sound space. The amplitude of the N1m exhibited tuning to the sound direction angle in both hemispheres, with response maxima and minima occurring for contralateral and ipsilateral stimuli, respectively. This contralateral preponderance of the amplitude of the N1m response is not surprising, given that connections between the ear and cortical hemisphere are crossed [18] and that previous brain research has demonstrated contralaterally larger auditory evoked electric [19] and magnetic [20-22] responses.

The present results also seem to suggest a degree of right-hemispheric specialization in the processing of auditory space. Firstly, the N1m of the right hemisphere was, on the average, of a considerably larger magnitude than that of the left hemisphere. Secondly, the right hemisphere appeared to be more sensitive to changes in the direction angle, with the variation of the amplitude of the N1m across direction angle being almost twice as large in the right hemisphere than in the left.

Previous behavioural studies have shown that natural-sounding spatial auditory environments can be created by using non-individualized HRTFs [23]. This is supported by our behavioural test, which showed that the HRTF-stimuli were localized relatively well by the subjects in all eight directions. Hence, already the use of non-individualized HRTFs provide realistic enough spatial sound conditions for MEG measurement purposes, although the extent of the use of HRTFs in MEG recording conditions remains to be established.

Sound localization is known to be easy for sound sources of wide frequency bandwidth [7]. Therefore, noise bursts with a frequency band of 11 kHz were used in the present study.

The present observations immediately suggest several follow-up studies which should provide further insight on sound location processing in the human brain. In addition to using noise bursts, a more wide range of stimulus types, such as speech signals (e.g., wovel sounds) and other periodic signals might provide important information on how different stimulus types are processed in the human brain. For example, the processing of speech is generally assumed to be lateralized to the left hemisphere in humans. Hovever, the role of natural hearing conditions (which seem to suggest a right-hemispheric preponderance in brain activity) in speech processing has not yet been addressed. Besides providing further observations on this issue in the near future [24], we also aim to explore the effect of non-individualized vs. individualized HRTFs in order to determine the extent of applicability and the possible restrictions in the use of HRTF-based stimulation in MEG recording conditions.

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