Late auditory evoked potentials to changes of ITD versus IPD

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Abstract

Specific binaural processing can be studied by analyzing late potentials (LAEPs) to changes of interaural parameters of noise stimuli, (e.g., McEvoy et al. 1991: "Effects of stimulus parameters on human evoked potentials to shifts in the lateralization of a noise", Audiology 30(5):286-302). The objective of the current study is to compare LAEPs to changes in interaural time difference (ITD) versus interaural phase difference (IPD) of low-frequency noise. The noises had center frequencies of 250, 500, 750 and 1000 Hz, the bandwidth was two octaves. Four values of the interaural parameters were used. For the IPD they were -135°, -45°, 45° and 135° degrees. The ITD-values were chosen to match the IPD-values for the center frequency of the respective noise bands. The duration of the stimuli was randomized between 800 and 850 ms. To avoid monaural cues, transitions between single stimuli were accomplished by crossfading neighboring stimuli with a 20 ms window. The running noise stimuli were presented to the subjects with 70 dB SPL via Etymotic ER2 insert earphones. The stimulus sequence comprised all possible 12 transitions of the four stimuli in pseudo-random order. 400 responses to each transition were averaged. For all stimuli, distinct late components P1, N1 and P2 with approximate latencies of 80, 130 and 200 ms, respectively, were observed. For all center frequenies, LAEPs were larger for IPD-changes compared to ITD-changes. Response amplitudes did not systematically vary with a specific source- or destination value of the ITD or IPD, but rather depended on the size of the change. For the IPD stimuli, the largest responses were evoked for 180° changes. For the ITD stimuli, an analog, albeit weaker response contrast was observed. LAEPs were largest for ITD-changes corresponding to the IPD-changes of 180°. For the band with a center frequency of 500 Hz, e.g., the ITD-changes of 1 ms (-0.25 to +0.75, -0.75 to +0.25 ms and vice versa) evoked larger LAEPs than all other ITD-changes. The results of the present study provide evidence to suggest a cyclic instead of a linear ITD representation in the auditory system.

Introduction

For more than half a century the prevailing paradigm to describe sound localization in the horizontal plane has been the model by Jeffress [3]. This model provides a place code for the interaural time difference (ITD) by means of bilaterally excitatory neurons connected to the monaural inputs via axonal delay lines. However, inconsistent with the Jeffress model, binaurally sensitive cells in the medial superior olive [1] and the inferior colliculus [4] of the mammalian auditory system have best ITDs that depend on their best frequency BF: best ITD ≈ 1/(8*BF) or best interaural phase difference IPD ≈ 45°, i.e., for a given BF there is no wide distribution of best ITDs as required in the Jeffress model.

The processing of interaural parameters in humans can be studied by means of late auditory evoked potentials (LAEPs) elicited by changes of interaural parameters of noise stimuli [2, 5, 6]. These potentials are specific responses of the binaural system since a monaural presentation of the stimuli does not evoke any response.

The objective of the present study is to address the question of the representation of IPD and ITD in the human auditory system by measuring LAEPs to IPD and ITD changes as a function of noise center frequency and bandwidth. The general assumption is that larger changes of interaural parameters evoke larger responses. Stimulus parameters were chosen such that IPD and ITD match at the center frequency of the noise band. For a dominant representation of the ITD, the responses should be maximal for the largest ITD change. If IPDs rather than ITDs are primarily represented in the auditory system, largest responses for an IPD change of 180° and for ITD changes corresponding to an IPD change of 180° are expected.

Methods

Stimulation

- Changes of dichotic bandpass noises with four IPDs = -135° ('L'), -45° ('l'), 45° ('r') and 135° ('R') or ITDs corresponding to the IPDs at the center frequency.
- The length of a single stimulus was chosen to be equally distributed from 800 to 850 ms.
- The stimulus sequence was: 'rRLlrLRlLrlRrRlrLlRLrlLR' and comprised all possible 12 transitions twice, the second half of the sequence being a mirror of the first half.
- Experiment 1: four center frequencies $f_c = 250$, 500, 750, 1000 Hz with bandwidth $\Delta f =$ two octaves.
- Experiment 2: three bandwidths $\Delta f = 67$, 200, 600 Hz at a center frequency $f_c = 500$ Hz.
- Presentation level: 70 dB SPL.

Recordings

- 6 normal hearing subjects
- 2 electrodes (A1, A2)
- For a given bandwidth and center frequency, LAEPs to IPD and ITD changes were measured alternatingly.
- Recording of 400 sweeps for each of the 12 transitions and 12 conditions took more than 13 hours measurement time for every subject.

Stimuli

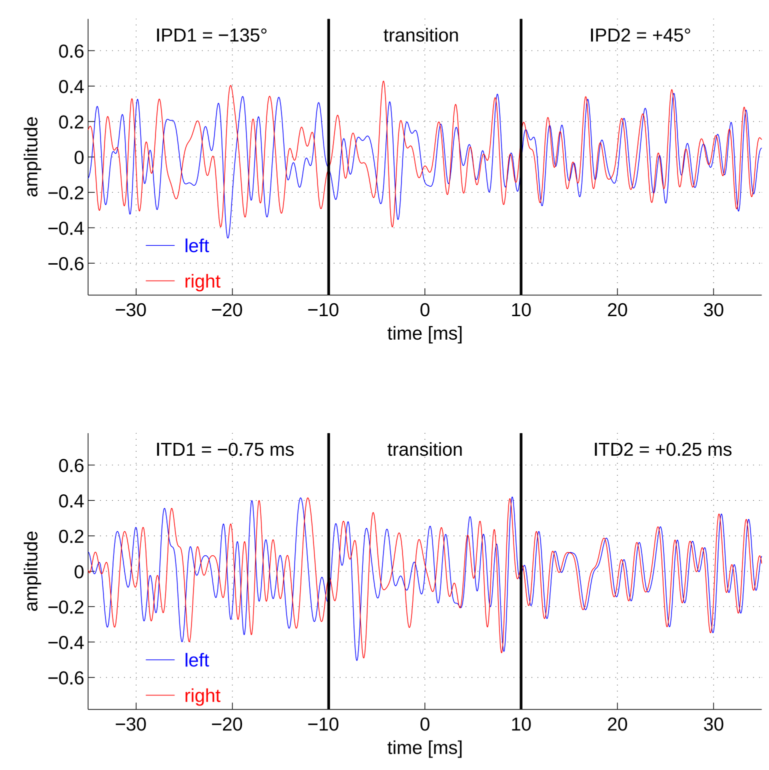

Fig. 1: Waveform examples of a bandpass noise with corner frequencies 200 and 800 Hz, i.e., $f_c = 500$ Hz, $\Delta f = 600$ Hz. The transitions or changes of the interaural parameters last 20 ms, long enough to avoid spectral artifacts. The transitions are accomplished by square-rooted Hanning windows to eliminate changes in presentation level. **Top row:** Transition from IPD1 = -135° to IPD2 = +45°. **Bottom row:** Transition from ITD1 = -0.75 ms to ITD2 = +0.25 ms. The ITDs are chosen to match the IPD at the center frequency $f_c = 500$ Hz.

LAEP to IPD changes

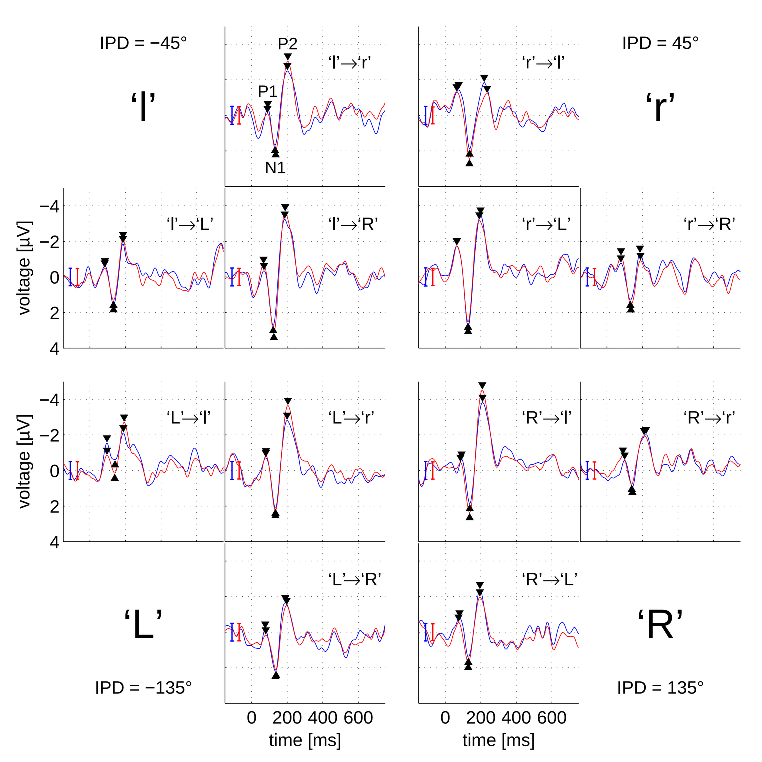

Fig. 2: LAEPs for the 12 IPD changes for the bandpass noise with 600 Hz bandwidth centered at 500 Hz. Data are for subject sc for both channels (A1 blue, A2 red). The errorbars denote $\pm\sigma$ (± S. E. M., a measure of residual noise based on single sweeps [7]). The triangles indicate LAEP peaks P1, N1 and P2. They roughly have latencies of 80, 130 and 200 ms, respectively. LAEPs to IPD transitions of 180° shown in the four central panels are larger than LAEPs evoked by IPD transitions of 90° depicted in the eight marginal panels.

LAEP to ITD changes

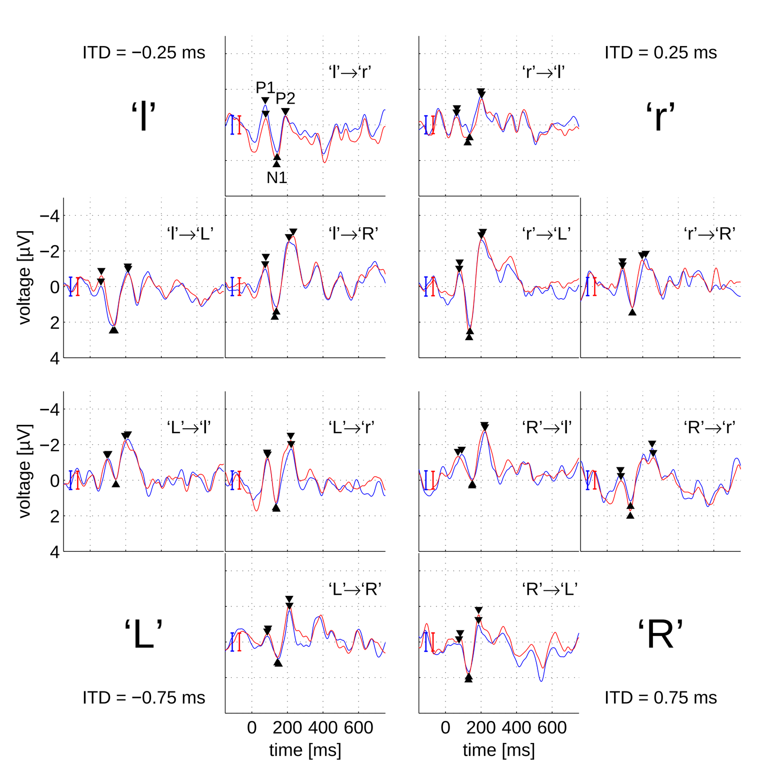

Fig. 3: LAEPs for the 12 ITD changes for the bandpass noise with 600 Hz bandwidth centered at 500 Hz presented in the same format as Fig. 2. Data are for subject sc for both channels (A1 blue, A2 red). ITD changes evoke smaller responses than the corresponding IPD changes. ITD transitions of 1 ms (central four panels) evoke larger LAEPs than ITD transitions of 0.5 ms (left two, upper two and right two panels) and 1.5 ms (lower two panels).

$\mathrm{A_{LAEP}(\Delta IPD, f_c)}$

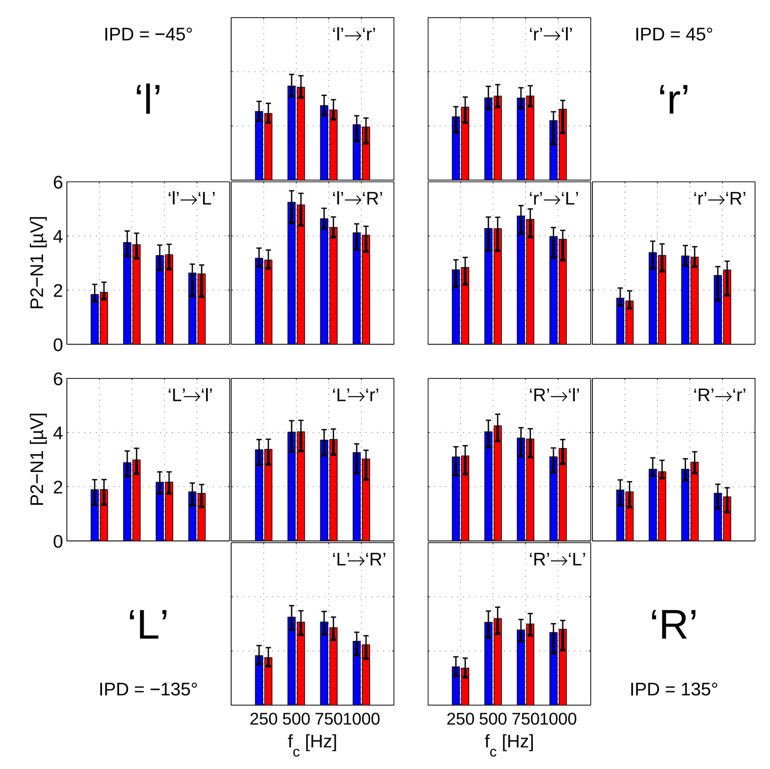

Fig. 4: LAEP amplitudes P2-N1 as function of the IPD change and the center frequency, mean over 6 subjects. Upper thin errorbars denote the mean standard error over the sweeps, lower thick errorbars the standard error over subjects. Amplitudes are larger for IPD changes of 180° compared to changes of 90°. IPD changes from IPD values of ±45° to IPD values of ±135° (2nd row) evoke larger LAEPs than vice versa (3rd row). In contrast, symmetrical changes from the left to the right side and vice versa yield similar LAEP amplitudes. LAEPs are larger for $f_c = 500$ and 750 Hz than for $f_c = 250$ and 1000 Hz.

$\mathrm{A_{LAEP}(\Delta IPD, \Delta f)}$

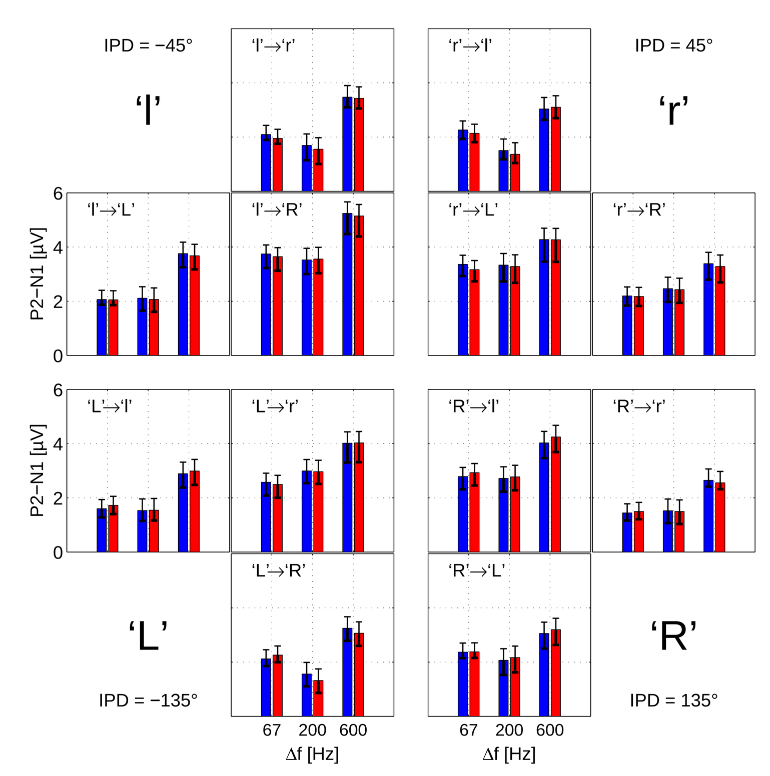

Fig. 5: LAEP amplitudes P2-N1 as function of the IPD change and noise bandwidth, mean over 6 subjects. Upper (lower) errorbars denote the standard error over the sweeps (subjects). As in Fig. 4, amplitudes are larger for IPD changes of 180° compared to changes of 90°, and IPD changes from more central to more peripheral percepts evoke larger LAEPs than vice versa. Again, symmetrical changes from the left to the right side and vice versa yield similar LAEP amplitudes. For most IPD changes, LAEP amplitudes increase with increasing bandwidth demonstrating a frequency integration effect for LAEPs.

Results

- LAEPs do not solely depend on the source (IPD1, ITD1) and destination (IPD2, ITD2) of the interaural parameters, but systematically depend on the size of the change of interaural parameters (ΔIPD, ΔITD).
- LAEP amplitudes are generally larger for IPD changes than for corresponding ITD changes.
- For IPD changes, LAEPs are largest for a change of 180°.
- For ITD changes, LAEPs are largest for a change corresponding to ΔIPD = 180° at the center frequency.
- For both, IPD and ITD changes, LAEPs are largest for the center frequencies of 500 and 750 Hz and decline at $f_c = 250$ and 1000 Hz (Figs. 4 and 6).
- For both, IPD and ITD changes, LAEPs increase with increasing bandwidth of the stimulus (Figs. 5 and 7).
- For all center frequencies and bandwidths tested, the ITD changes 'l' to 'L' and 'r' to 'R', i.e., from a more central to a more lateral percept, yield larger LAEPs than the changes 'L' to 'l' and 'R' to 'r', respectively. This also holds for IPD changes, albeit with a weaker contrast as for ITD changes.
- For all center frequencies and bandwidths tested, the largest ITD changes 'L' to 'R' and 'R' to 'L' evoke smaller LAEPs than the ITD changes 'l' to 'R' and 'r' to 'L'.

$\mathrm{A_{LAEP}(\Delta ITD, f_c)}$

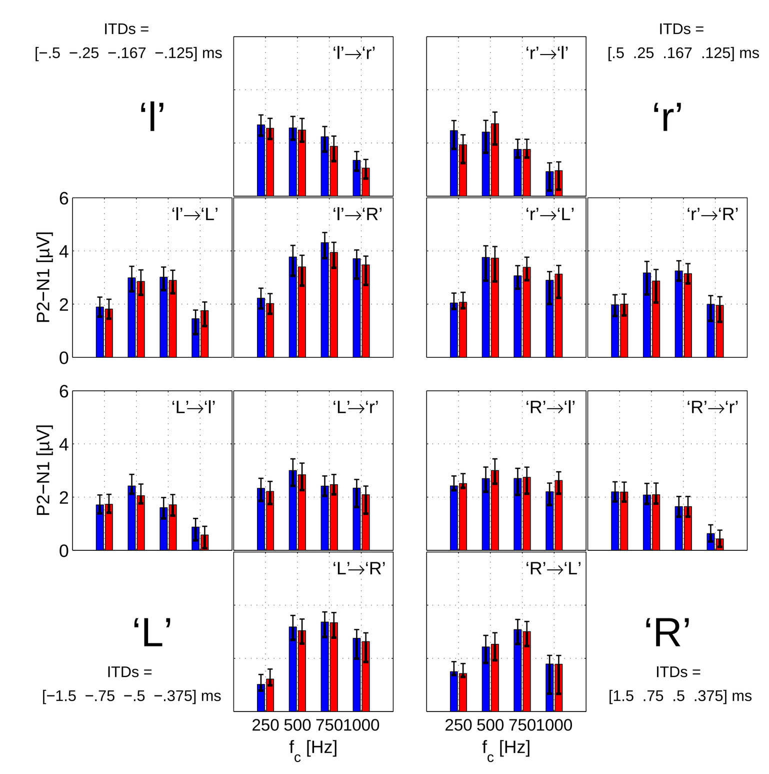

Fig. 6: LAEP amplitudes P2-N1 as function of the ITD change and the center frequency, mean over 6 subjects. Upper (lower) errorbars denote the standard error over the sweeps (subjects). LAEP amplitudes evoked by ITD changes are smaller than LAEP amplitudes for the corresponding IPD transitions (Fig. 4). Amplitudes are largest for ITD changes corresponding to an IPD change of 180°. ITD changes from small absolute ITDs (more central percepts) to larger absolute ITDs (more lateral percepts) evoke larger LAEPs than vice versa. LAEPs tend to be larger for $f_c = 500$ and 750 Hz than for $f_c = 250$ and 1000 Hz.

$\mathrm{A_{LAEP}(\Delta ITD, \Delta f)}$

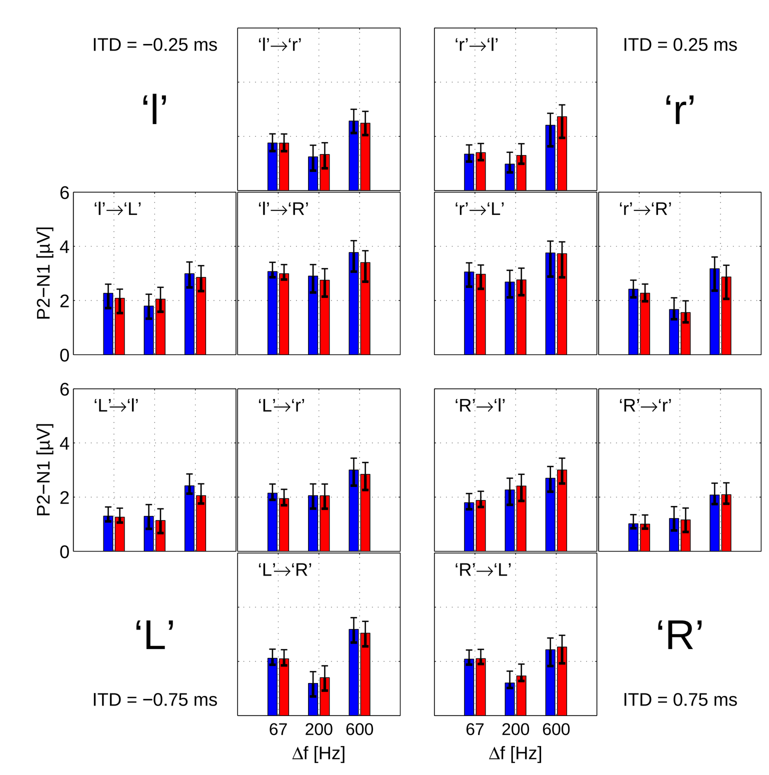

Fig. 7: LAEP amplitudes P2-N1 as function of the ITD change and noise bandwidth, mean over 6 subjects. Upper (lower) errorbars denote the standard error over the sweeps (subjects). LAEP amplitudes evoked by ITD changes are smaller than LAEP amplitudes for the corresponding IPD transitions. As in Fig. 5, amplitudes are largest for ITD changes corresponding to an IPD change of 180°, and ITD changes from small absolute ITDs (more central percepts) to larger absolute ITDs (more lateral percepts) evoke larger LAEPs than vice versa. For most ITD changes, LAEP amplitudes increase with increasing bandwidth.

Conclusions

- Since the largest ITD changes did not yield the largest LAEP amplitudes, a linear representation of the ITD as, e.g., in the Jeffress model, is not plausible.
- The similar response patterns for IPD and ITD changes, even for a bandwidth of two octaves, support the hypothesis of a cyclic representation of the ITD in the auditory system.

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