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Chirp evoked binaural difference potentials

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Introduction

For more than half a century the prevailing paradigm to describe sound localization in the horizontal plane has been the model by Jeffress [7]. It uses a chain of coincidence detector cells which receive bilateral excitatory inputs in an ordered network of delay lines. The model provides a place code for the sound azimuth by means of the ITD (interaural time difference). However, for cells in the medial superior olive (MSO) of the mammalian auditory system it was recently found that the best interaural phase difference (IPD) for binaurally sensitive cells is about one eighth ($\pi/4$) of the stimulus period for all stimulus frequencies, i.e., there is no distribution of IPDs (or ITDs) as required in the Jeffress model [10]. Precise contralateral inhibition is needed and ITD coding is performed by a rate code rather than a place code [1].

This study deals with human sound localization and analyzes the dependence of auditory brain stem responses (ABRs) on the ITD.

In evoked response studies, binaural interaction is commonly assessed in terms of the binaural difference potential, symbolically BD = B – (L + R). [5, 9, 15, 2, 13, 14].

Rising frequency chirps evoke a larger monaural ABR than clicks because they compensate for the dispersion along the basilar membrane [3]. In the first experiment BDs evoked by clicks and chirps are compared.

The first major peak in the BD, DN1, is believed to be a physiological correlate of the categorial percept of binaural fusion [5, 4]. In [5, 2] an approximately constant DN1 amplitude for ITDs up to 1 ms was found. For ITDs longer than 1.2 ms DN1 was undetectable [5]. In contrast, other studies reported a gradually decreasing DN1 amplitude with increasing ITD, the BD became undetectable for ITD > 1.6 ms [8, 11]. The second experiment analyzes the ITD-dependence of chirp-evoked BDs.

Methods

- 10000 sweeps per condition were averaged to obtain the ABR.
- The residual noise was estimated on a single-sweep-basis as the standard error over the sweeps [12].

Experiment 1 – Comparison click versus chirp

- 2 stimuli, see Fig. 1
  - a click of 0.1 ms duration
  - a chirp of 10.3 ms duration with flat spectrum and corner frequencies 100 and 10000 Hz
- 10 normal hearing subjects
- 6 levels from 10 to 60 dB nHL in steps of 10 dB
- 3 channels (A1, A2, IZ)

Experiment 2 – ITD-dependence of the BD

- Stimulus: flat spectrum chirp at 40 dB nHL
- 17 ITDs: 0 to 1.5 ms in steps of 0.1 ms, additionally 2 ms
- 40000 sweeps were averaged for the monaural conditions.
- 11 normal hearing subjects
- 4 channels (A1, A2, PO9, PO10)

Experiment 1 – Comparison click versus chirp

Stimuli

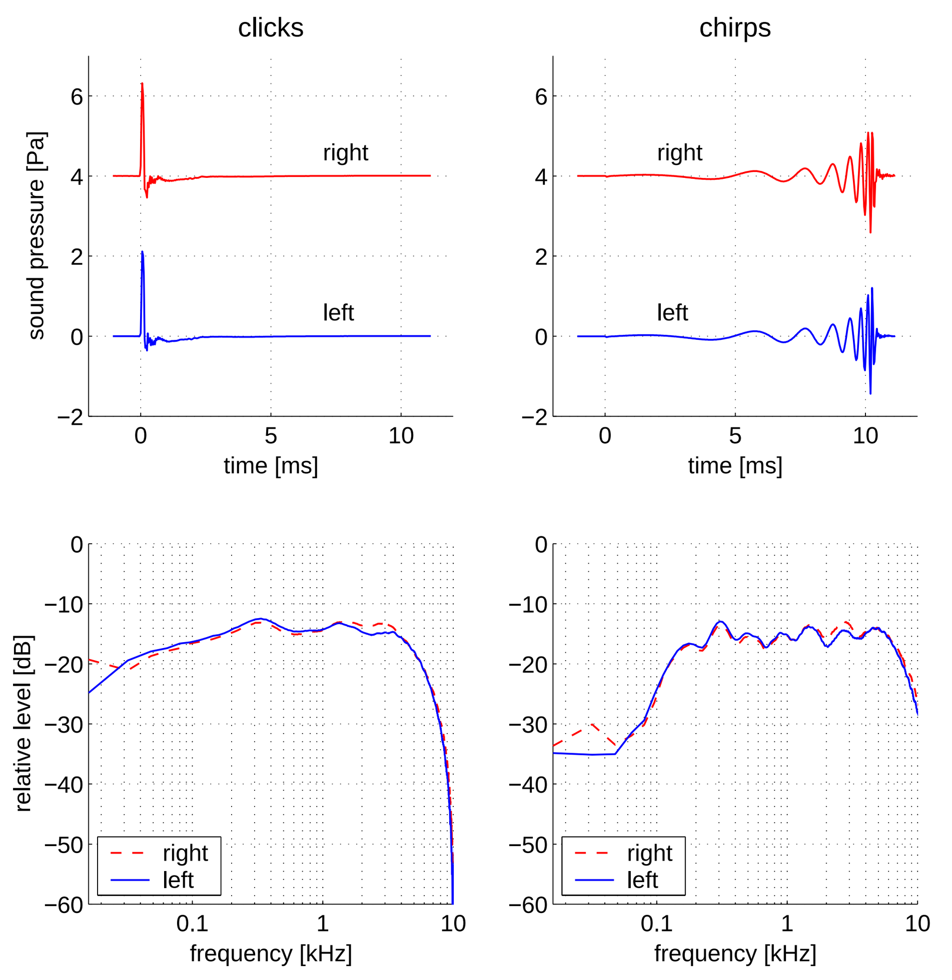

Fig. 1: Top row: Acoustic waveforms of the click (left panel) and the chirp (right panel) measured at 60 dB nHL, corresponding to 100.5 dB peSPL for the click and 97 dB peSPL for the chirp, respectively. Right stimuli are plotted with an offset of 4 Pa. **Bottom row:** Acoustic spectra of the stimuli using 625 FFT bins in steps of 80 Hz. The envelope of the chirp was designed to result in a flat spectrum in the frequency range from 100 to 10000 Hz mimicking the spectrum of the click.

BD recordings for various levels

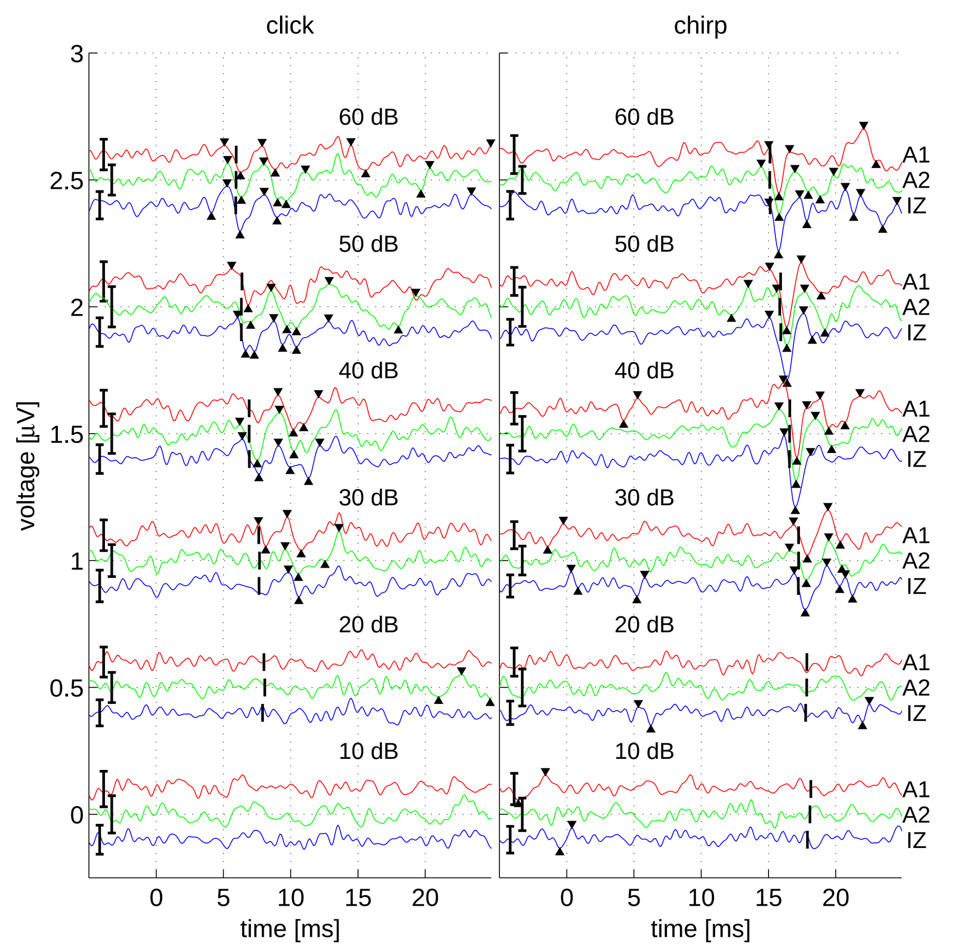

Fig. 2: BDs for clicks and chirps for 6 stimulus levels, subject rh. Plot offset between channels is 0.1 μV, plot offset between stimulus levels is 0.5 μV. Errorbars denote $\pm 3\sigma$ (± 3 S. E. M.). The triangles indicate peak pairs whose peak-to-peak values exceed $\sqrt{2}\cdot 3\sigma$. Vertical bars denote the latency of the binaural wave V.

BD amplitude

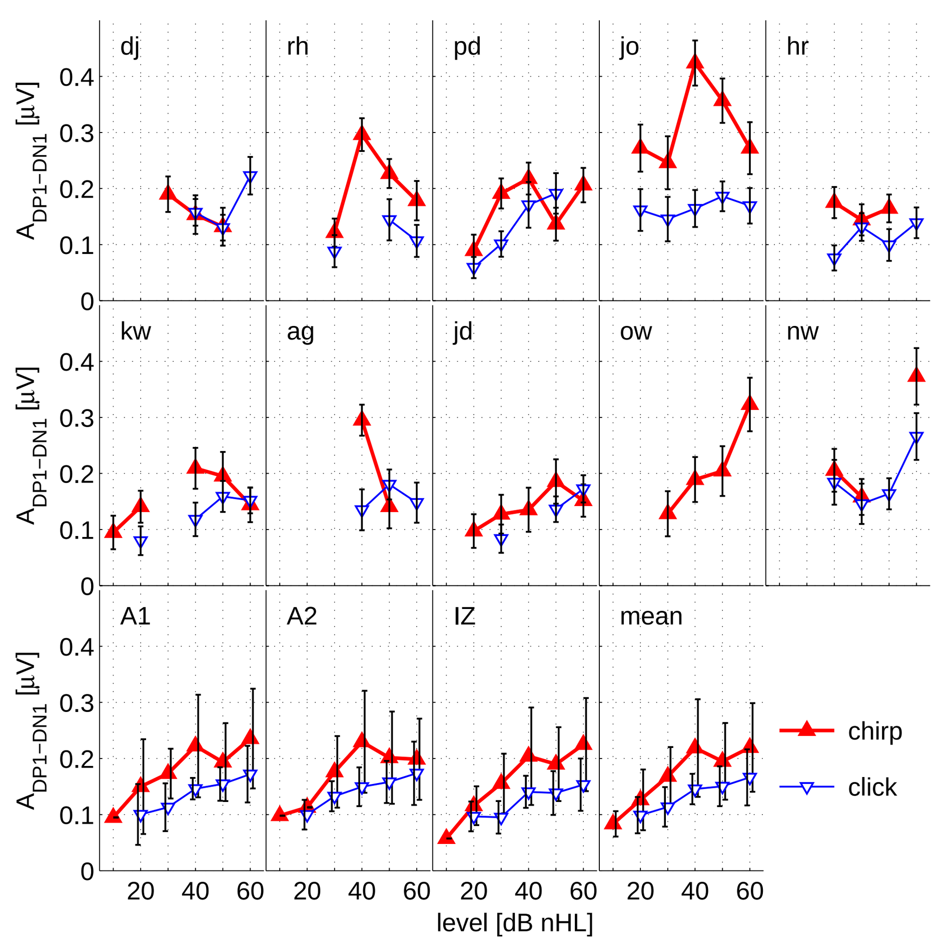

Fig. 3: BD amplitude $A_{DP1-DN1}$ as function of the stimulus level. **Top and middle row:** data for single subjects from channel A1 with intraindividual standard errors ($\pm\sqrt{2}\cdot\sigma$). For five subjects, the chirp BD is maximal at 40 dB nHL, for the other subjects chirp BDs level off or increase further. **Bottom row:** data averaged over subjects with interindividual standard deviations, channels A1, A2, IZ and mean over channels. The dependence of $A_{DP1-DN1}$ on stimulus type and level is similar for all channels: chirp BDs grow faster with stimulus level than click BDs and level off at 40 dB nHL.

Amplitude ratio BD/B

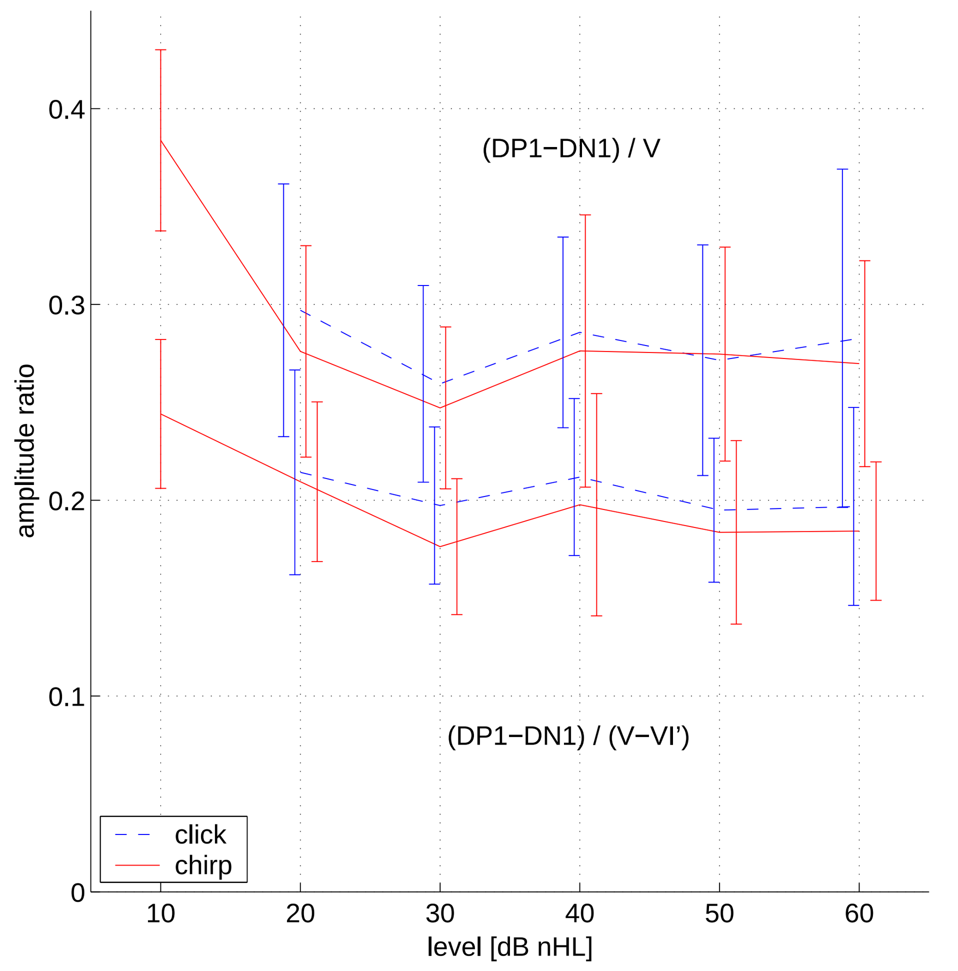

Fig. 4: Amplitude ratio of the BD to the binaural response B, mean data and standard deviations over 10 subjects and 3 channels. In the upper two curves the binaural wave V amplitude is measured baseline-to-peak, in the lower curves peak-to-peak from wave V to VI' (trough after VI). The constant amplitude ratio is compatible with contralateral inhibitory and ipsilateral excitatory (IE) interaction. In contrast, with bilateral excitatory (EE, Jeffress) interaction, the non-linearity after the summation of left and right input to obtain a BD would lead to a level-dependent amplitude ratio BD/B [6].

Experiment 2 – ITD-dependence of the BD

BD recordings for various ITDs

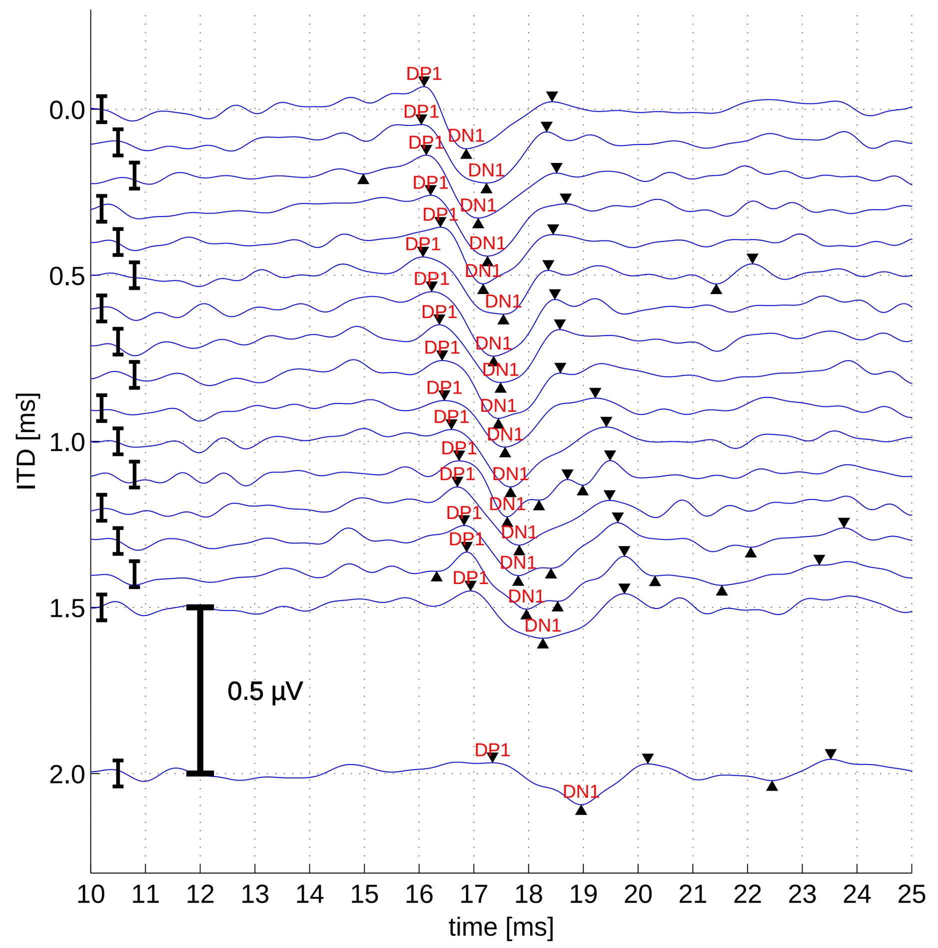

Fig. 5: BDs in dependence on the ITD: data from channel PO10 of subject rb. The errorbars denote $\pm 3\sigma$ (± 3 S. E. M.). The triangles indicate peak pairs whose peak-to-peak values exceed $\sqrt{2}\cdot 3\sigma$. The time axis is plotted relative to stimulus onset. Significant binaural interaction is found for all ITDs tested.

BD amplitude

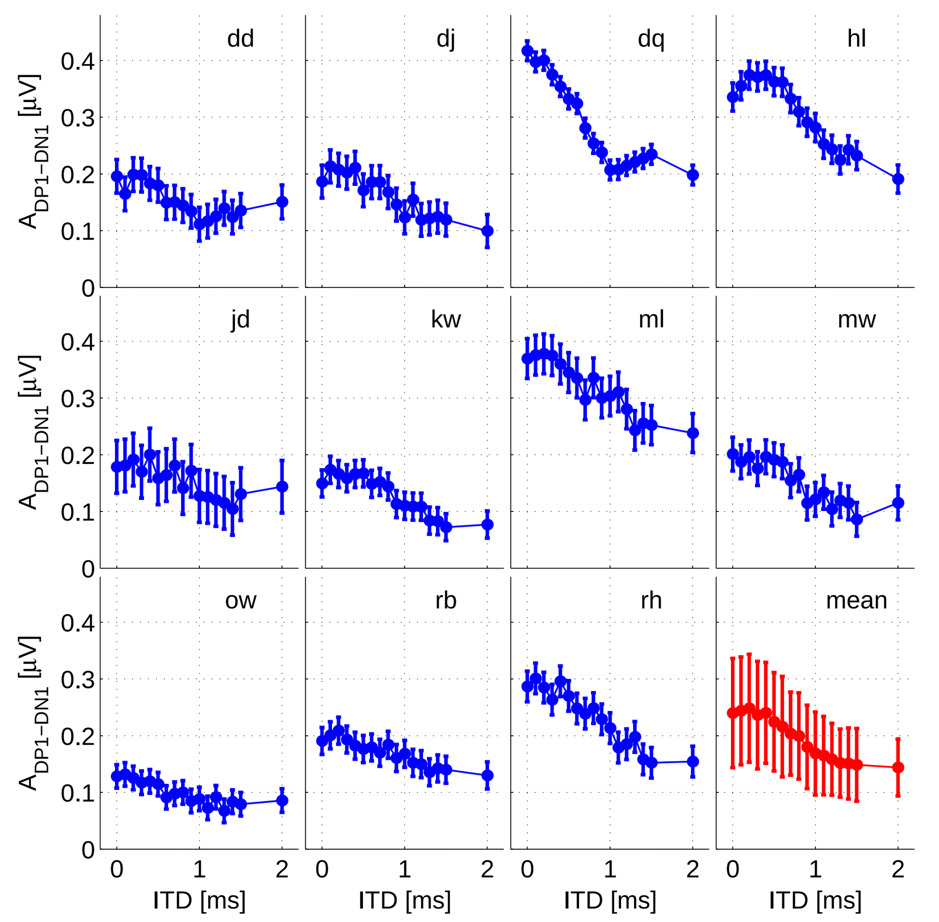

Fig. 6: Mean amplitude of BD-wave DP1-DN1 averaged over channels as function of the ITD. The first 11 subplots show single subject data, the errorbars indicate intraindividual standard errors ($\pm\sqrt{2}\cdot\sigma$). The last subplot depicts the mean over subjects, the errorbars denote ± 1 standard deviation. The BD amplitude decreases with increasing ITD. The maximum around an ITD of 0.2 ms for many subjects and the mean data is not significant. It is not due to inaccuracies in the stimulation system.

BD latency

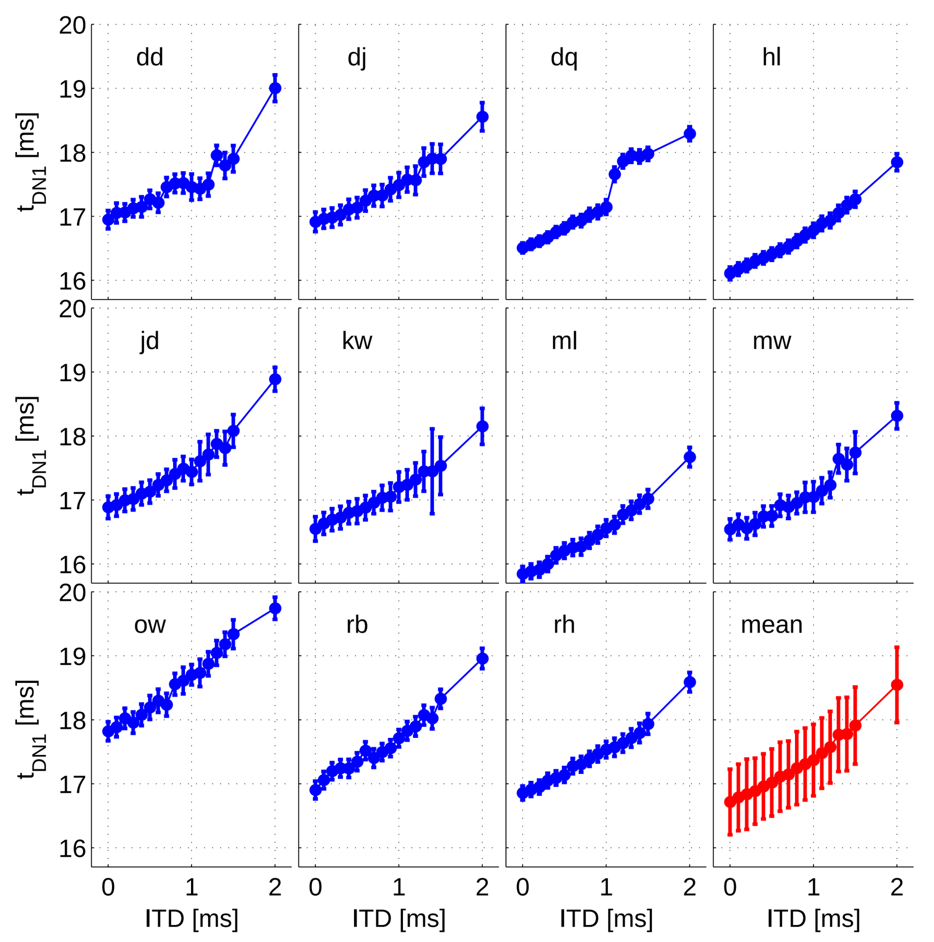

Fig. 7: Mean latency of BD-wave DN1 averaged over channels as function of the ITD. The first 11 subplots show single subject data, the errorbars indicate $\pm 3\sigma$ (± 3 S. E. M.). The last subplot depicts the mean over subjects, the errorbars denote ± 1 standard deviation. The shortest latency is always found for diotic stimulation, DN1 latency is monotonically increasing with increasing ITD. Latencies are measured from stimulus onset.

Mean relative DN1 latency

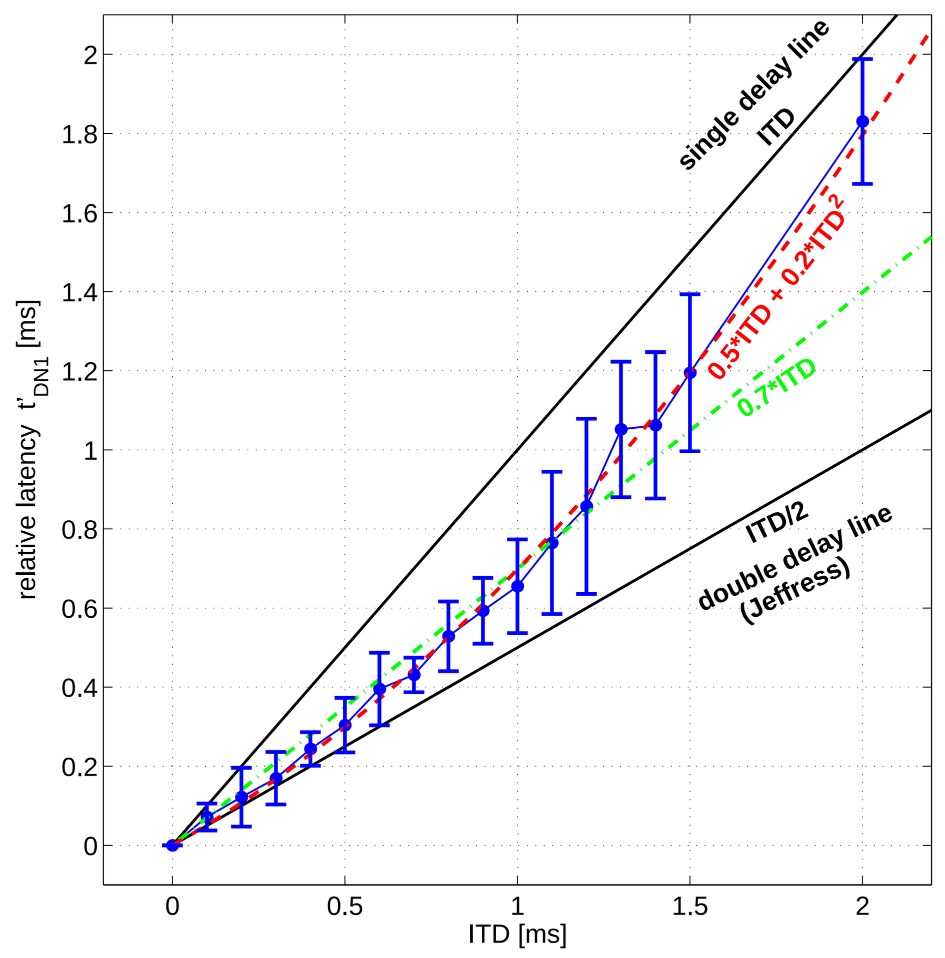

Fig. 8: Mean relative latency of BD-wave DN1 averaged over channels as function of the ITD ($t'_{DN1} = t_{DN1} - t_{DN1,ITD=0}$). Errorbars denote ± 1 standard deviation. The lower solid line indicates the latency due to the Jeffress model [8]. The upper straight line is for a modified Jeffress model using a single unilateral delay line [15]. The dash-dotted line is the outcome of a linear χ^2-fit (one parameter). The dashed line holds for a quadratic χ^2-fit (two parameters).

Results

Experiment 1 – Comparison click versus chirp

- Larger BD amplitude for chirps than for clicks (Fig. 2, 3)
- Steeper growth functions for chirps up to 40 dB nHL (Fig. 3)
- Maximal amplitude difference at 40 dB nHL (Fig. 3)
- Significant differences for 30, 40 dB nHL (Wilcoxon rank test)
- Independence of the amplitude ratio BD/B from level (Fig. 4)

Experiment 2 – ITD-dependence of the BD

- Significant BD for ITDs up to 2 ms (Fig. 5, 6)
- Decreasing BD amplitude with increasing ITD (Fig. 5, 6)
- Increasing BD latency with increasing ITD (Fig. 5, 7)
- Relative BD latency $t'_{DN1} = t_{DN1} - t_{DN1,ITD=0}$ is growing faster than ITD/2, but slower than ITD (Fig. 8)
- Linear χ^2-fit: $t'_{DN1} = 0.70$ ITD (goodness-of-fit = 0.62)
- Quadratic χ^2-fit: $t'_{DN1} = 0.50$ ITD + 0.20 ITD^2 (ITD in ms, goodness-of-fit = 0.999998)

Conclusions

- The advantage of larger chirp-evoked ABRs in comparison to the click is also found for the BD.
- The constant amplitude ratio BD/B demonstrates the dominance of IE-interaction.
- The current findings are inconsistent with the Jeffress model:
  - BDs are detectable for ITDs up to 2 ms, far outside the physiological range.
  - The latency increase in the Jeffress model is ITD/2 [8, 15], but the relative DN1 latency grows faster than ITD/2.

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