# On the precision of neural computation with interaural time differences in the medial superior olive

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## Abstract

We study a model of mammalian sound source localization in horizontal plane. Experiments on small rodents indicate that mammals use broadly tuned channels of azimuth for localization in horizontal plane. In mammals this neural computation is implemented by medial superior olive for low frequency sounds up to 1500 Hz. It has been shown previously that spike timing jitter, coincidence detection window length, sound frequency, among other input parameters, influence the output precision, measured by the just noticeable difference in output of the circuit. We use stochastic model with spiking neurons. We explore variations of the parameters mentioned above. We calculate properties of the model with the use of analytical methods. Predictions of this model have straightforward applications in testing and designing stimulation protocols used in cochlear implants.

*Keywords:* binaural hearing, coincidence detection, ergodic hypothesis, ideal observer, interaural time difference, just noticeable difference, medial superior olive, neuronal arithmetic, sound localization

### 1. Introduction

Mammalian sound localization circuits contain two nuclei in the auditory brainstem, the medial and the lateral superior olive (MSO and LSO). Neurons in these

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nuclei are the first binaural neurons in the auditory pathway, they are connected to both ears.

This article presents description of information encoding and neural computation in the MSO obtained mostly with analytical computations. Using the analytical tools we extend quantitative results obtained by Sanda and Marsalek (2012) only in simulations and connect them to Bures and Marsalek (2013) to arrive to unified description of neural circuits in the superior olive. We use this description to find maximum spike timing precision attained by the following two respective modalities (low and high frequency sound localization) of natural and electrical hearing.

Due to the physical nature of the binaural sound, the MSO neurons process spike timing differences in the range of tens of microseconds, $\mu$s. The MSO processes low frequency sounds, in human this is from 20 Hz to not more than 2 kHz. The LSO processes high frequency sounds, in human this is from 1 kHz up to 20 kHz. The overlapping region is known to have a sensitivity drop at 1.5 kHz Mills (1958).

Firing rate, first spike latency and individual spike timings are used in neural system coding, especially in the auditory pathway. The highest known spike timing precision that has been proven to be utilized in the mammalian auditory system is the motor response in a bat. In behavioral experiment, the big brown bat, *Eptesicus fuscus* catches tidbit larvae of the meal-worm beetle *Tenebrio molitor*. The motor precision is in the range of hundreds of nanoseconds, ns, and auditory separation of ultrasound echoes is in the order of microsecond units, 1 $\mu$s Simmons et al. (1998). Comparable performance of the human MSO is in the range of microseconds, 10 $\mu$s and can be improved after several hours of training.

Different neural mechanisms are employed in the two nuclei.

It has been reported that computation in the MSO is independent on sound intensity Grothe et al. (2010). With higher sound intensity, first spike latency is shortening. Relation of this dependence to ITD and ILD has been described, yet it is difficult to interpret. Michelet et al. (2012) have shown the latencies in experiment on the domestic cat, *Felis silvestris*.

The LSO and MSO extract location information with the use of different physical cues. The sensitivity of the system in dependence on the main sound frequency to sounds of different main frequencies should be different. In human, MSO is the larger of the two nuclei and contains approximately 15500 neurons, Yet another neuronal arithmetic: Koutsou et al. (2012).

This is about other dimension; if we cite this, then we must discuss all the three, Kopco et al. (2012). hall we do that?

Jitter and variability... : Kostal and Marsalek (2010).

This is a chronological record of the neuronal arithmetic ideas, starting from: Marsalek (2000), through Marsalek (2001) some more detailed account o the diversity of cell functions and shapes: Reed et al. (2002), through Marsalek and Kofranek (2004) to the Marsalek and Kofranek (2005); watch the years ...

Remains to be cited: no-cites of Smith et al. (1993).

Next Cariani (2011), Bouse et al. (2019), Bures (2014), Michelet et al. (2012), Srinivasan et al. (2018).

## Conclusions

This theoretical paper is a followup of sound localization precision descriptions in the MSO Sanda and Marsalek (2012) and in the LSO Bures and Marsalek (2013). Novel results are two: 1) analytical estimates of results obtained previously only by numerical simulation and 2) comparison of natural and electrical hearing modalities and demonstrating what is the maximum timing precision which can be attained by the two modalities.

## Notes

Marek Hajny can join the author team as: middle position author with tasks: 1) to compile Discussion and write and 2) to rewrite parts of the manuscript.

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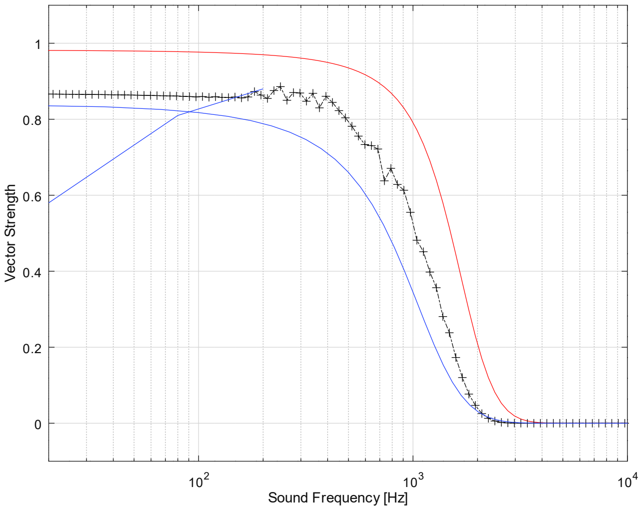

Figure 1: **Vector strength of auditory nerve spike trains in dependence on sound frequency.** X-axis shows fundamental sound frequency in Hz in a logarithmic scale and y-axis shows the vector strength. Even though is some nuclei up the auditory pathway the synchronization can be maintained towards higher frequencies than shown here, the decrease of the vector strength towards higher frequencies is a general property of all neurons in the auditory pathway.

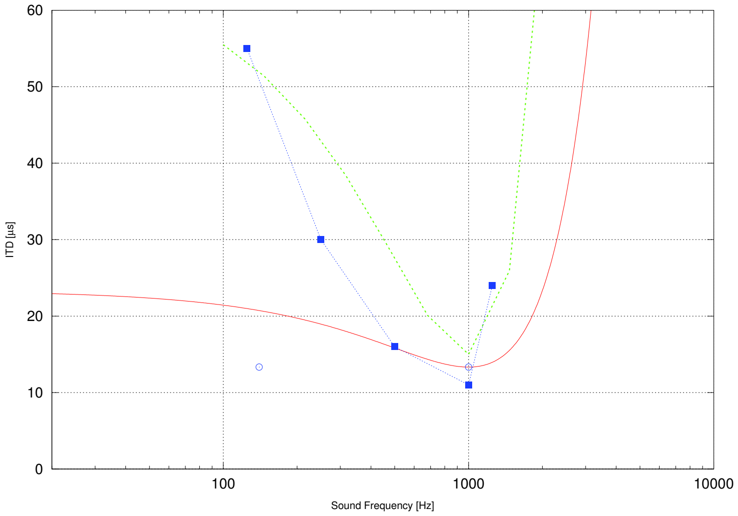

Figure 2: **The shortest ITD detected in the dependence on sound frequency.** X-axis shows sound frequency in Hz in a logarithmic scale and y-axis the shortest JND in $\mu$s. This is a theoretical prediction based on the analytical model and basic parameter set used in previous simulations.

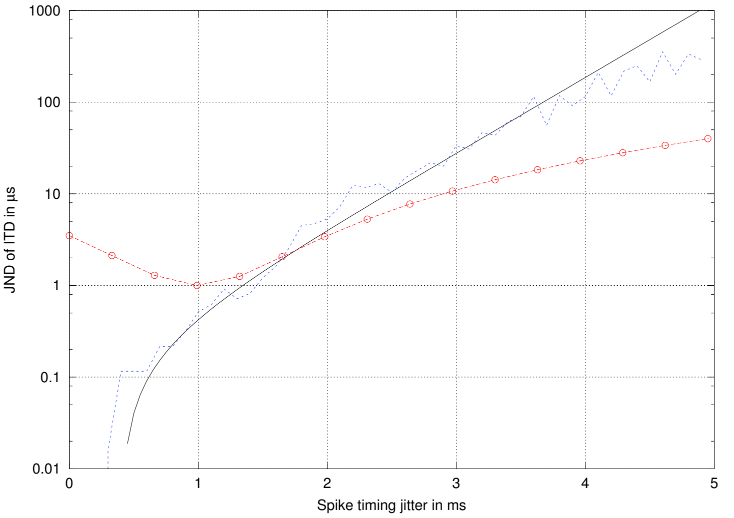

Figure 3: **The JND values in basic parameter set in dependence on the jitter magnitude.** This plot in semi-logarithmic y-scale shows just noticeable difference of interaural time difference depending on variation of the spike timing jitter. Jagged line: simulated data, solid line: an exponential fit to the simulations under the assumption of arbitrary time precision in the model circuit, line with circles: a quadratic function estimate of spike timing precision in a system with addition of noise.

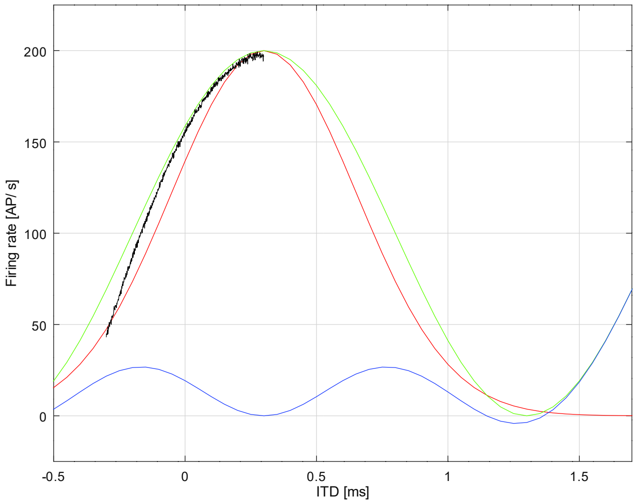

Figure 4: **Gaussian fit of the ITD to firing rate slope calibration curve.** X-axis shows ITD in ms and y-axis shows corresponding firing rate in action potentials per second. Note that the curve peak is offset from the origin of coordinates at $t_{\mathrm{ITD}} = 0$.

| Parameter | Symbol | Units | Typical Value | Ranges |
|---|---|---|---|---|
| Jitter | $T_J = \sigma$ | ms | 1 | 0.125 - 8 |
| Window | $w_{CD}$ | ms | 0.6 | 0.15 - 1.5 |
| Sound Frequency | $f$ | Hz | 200 | 40-1600 |
| | | | | |

Table 1: The basic set of parameters.

| Parameter | Symbol | Units | 4× Slower | Values (man) | 4× Faster | 16× Faster |
|---|---|---|---|---|---|---|
| Sound frequency ranges | $f$ | Hz | 17.5 - 110 | 70 - 440 | 280 - 1760 | 1120 - 7040 Hz |
| Window size | $w_{CD}$ | $\mu$s | 2400 | 600 | 150 | 37.5 |
| Timing Jitter | $T_{\mathrm{J}}$ | ms | 4 | 1 | 0.25 | 62.5 $\mu$s |
| Predicted JND | $T$ | $\mu$s | 40 | 10 | 2.5 | N/ A |
| Predicted detection time* | $T$ | ms | 2,600 | 650 | 162.5 | N/ A |

Table 2: TODO add the last OVERLAPPING band 4480 - 28160 and make all a bit narrower to start at 20 Hz and end at 20000 Hz. This Table is direct scaling of parameters used in Sanda and Marsalek (2012). Make also MSO and LSO entries...
Predicted values are: 1) just noticeable difference (JND) of the ITD 2) the time of observation by an ideal observer reading the information from one neuron.