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Research Paper

A probabilistic Poisson-based model accounts for an extensive set of absolute auditory threshold measurements

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ABSTRACT

Thresholds for detecting sounds in quiet decrease with increasing sound duration in every species studied. The neural mechanisms underlying this trade-off, often referred to as temporal integration, are not fully understood. Here, we probe the human auditory system with a large set of tone stimuli differing in duration, shape of the temporal amplitude envelope, duration of silent gaps between bursts, and frequency. Duration was varied by varying the plateau duration of plateau-burst (PB) stimuli, the duration of the onsets and offsets of onset-offset (OO) stimuli, and the number of identical bursts of multiple-burst (MB) stimuli. Absolute thresholds for a large number of ears (>230) were measured using a 3-interval-3-alternative forced choice (3I-3AFC) procedure. Thresholds decreased with increasing sound duration in a manner that depended on the temporal envelope. Most commonly, thresholds for MB stimuli were highest followed by thresholds for OO and PB stimuli of corresponding durations. Differences in the thresholds for MB and OO stimuli and in the thresholds for MB and PB stimuli, however, varied widely across ears, were negative in some ears, and were tightly correlated. We show that the variation and correlation of MB-OO and MB-PB threshold differences are linked to threshold microstructure, which affects the relative detectability of the sidebands of the MB stimuli and affects estimates of the bandwidth of auditory filters. We also found that thresholds for MB stimuli increased with increasing duration of the silent gaps between bursts. We propose a new model and show that it accurately accounts for our results and does so considerably better than a leaky-integrator-of-intensity model and a probabilistic model proposed by others. Our model is based on the assumption that sensory events are generated by a Poisson point process with a low rate in the absence of stimulation and higher, time-varying rates in the presence of stimulation. A subject in a 3I-3AFC task is assumed to choose the interval in which the greatest number of events occurred or randomly chooses among intervals which are tied for the greatest number of events. The subject is further assumed to count events over the duration of an evaluation interval that has the same timing and duration as the expected stimulus. The increase in the rate of the events caused by stimulation is proportional to the time-varying amplitude envelope of the bandpass-filtered signal raised to an exponent. We find the exponent to be about 3, consistent with our previous studies. This challenges models that are based on the assumption of the integration of a neural response that is directly proportional to the stimulus amplitude or proportional to its square (i.e., proportional to the stimulus intensity or power).

1. Introduction

The detection of sounds in quiet is arguably the simplest task performed by an auditory system, but the underlying mechanisms are still a matter of debate. The threshold for detecting a sound in quiet (often referred to as the 'absolute threshold') is commonly defined as the sound level required for a subject to report that sound in a specified proportion of presentations. For a given sound carrier, threshold decreases with increasing duration of the sound in every species capable of hearing, from insects to humans. Fig. 1a shows thresholds compiled from the literature for a range of

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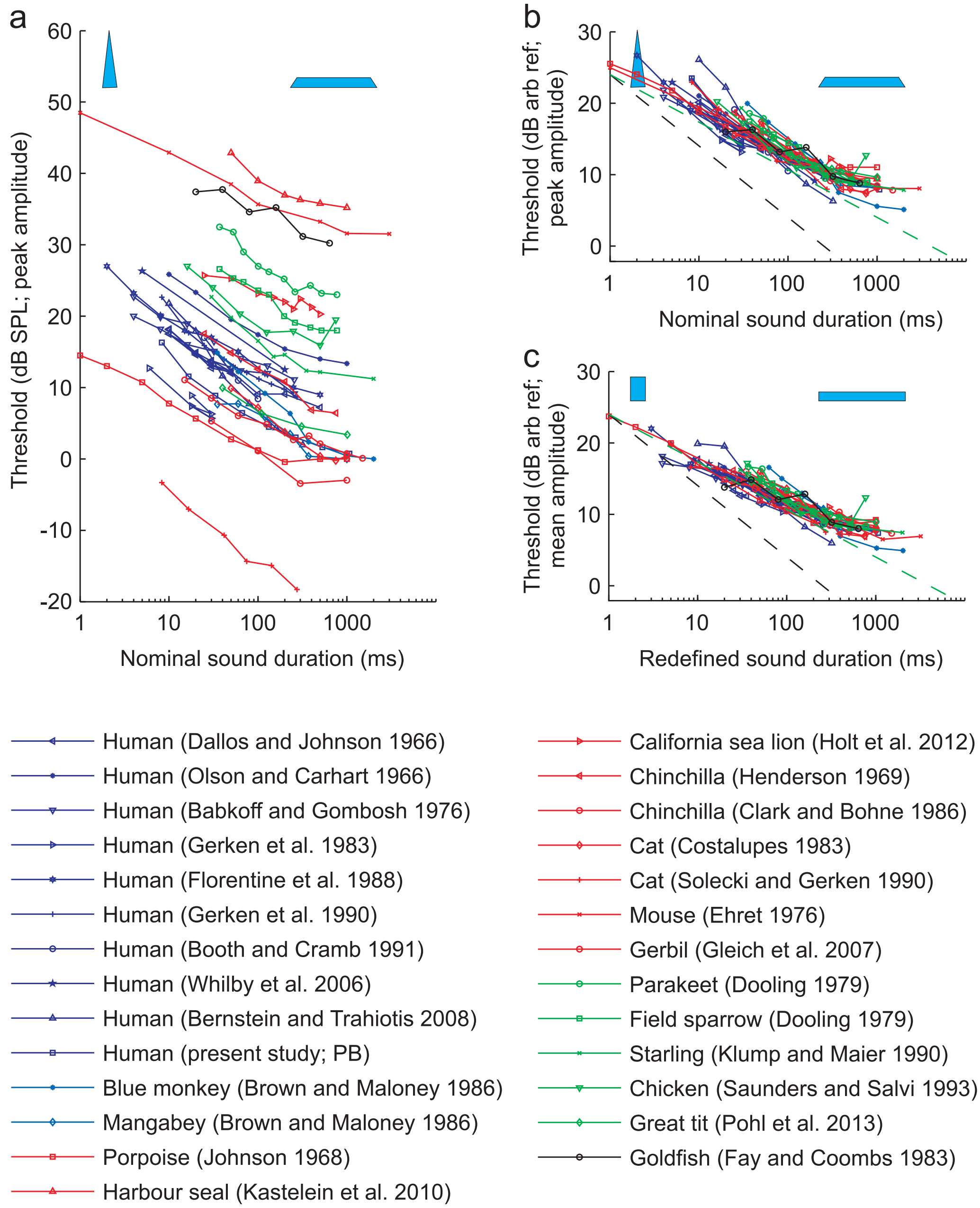

Fig. 1. a. Threshold vs. sound duration functions from various vertebrate species, as reported in the literature. Human data are from Dallos and Johnson (1966; 1 kHz), Olson and Carhart (1966; mean across three frequencies and noise), Babkoff and Gombosh (1976; noise), Gerken et al. (1983; 2 kHz), Florentine et al. (1988; 4 kHz), Gerken et al. (1990; 3.125 kHz), Booth and Cramb (1991; 1 kHz), Whilby et al. (2006; 1 kHz), Bernstein and Trahiotis (2008; 0.5 kHz; mean of So and Sπ conditions), and the present study (3.125 kHz, plateau-burst stimuli); non-human primate (blue monkey and mangabey) data from Brown and Maloney (1986; mean across four frequencies); porpoise data from Johnson (1968; mean across two frequencies); harbor seal data from Kastelein et al. (2010; mean across six frequencies; thresholds expressed with respect to 20 μPa rather than to 1 μPa); sea lion data from Holt et al. (2012; mean across three frequencies); chinchilla data from Henderson (1969; 2 kHz) and Clark and Bohne (1986; mean across five frequencies); cat data from Costalupes (1983; mean across three frequencies) and Solecki and Gerken (1990, 6.25 kHz); mouse data from Ehret (1976; mean across 12 frequencies); gerbil data from Gleich et al. (2007; 2 kHz); parakeet and sparrow data from Dooling (1979; 2.86 kHz); starling data from Klump and Maier (1990; mean across four frequencies); chicken data from Saunders and Salvi (1993; mean across 12 frequencies); great tit data from Pohl et al. (2013; mean across three frequencies); goldfish data from Fay and Coombs (1983; 0.4 kHz). The relative contribution of onset and offset durations to the total sound duration is greater for shorter, higher-amplitude sounds (blue triangle) than for longer, lower-amplitude sounds (blue trapezoid). **b**. Thresholds from the same studies as in **a** after vertically shifting each curve to obtain close overlap. The dashed black and green lines have slopes of −20/2 dB per tenfold increase in duration and −20/3 dB per tenfold increase in duration, respectively. **c**. Thresholds from the same studies as in **a**, but expressed with respect to the mean amplitude rather than the peak amplitude of the sounds and plotted against the sound duration from the beginning of the onset to the end of the offset. The curves were vertically shifted using the same procedure as for **b**. The blue rectangles at the top indicate the respective mean heights of the triangle and trapezoid in **a** and **b**. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vertebrate species. Thresholds for sounds of different carriers from a given study were averaged to reduce noise, because there is little evidence that frequency has a systematic effect on the slope of the threshold vs. duration functions for tones in quiet (see, e.g., Brown and Maloney, 1986), unlike for tones in broadband noise (Dai and Wright, 1996). Fig. 1b shows the same data after shifting the curves vertically so they overlap closely (see 2.6). Although there is some scatter between different data sets, particularly at shorter