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Review

Contributions of von Békésy to psychoacoustics

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A R T I C L E I N F O

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A B S T R A C T

This paper reviews the contributions of von Békésy to psychoacoustics, comparing his findings and interpretations to those that have emerged since his work. The areas covered include the perception of pitch for pure tones and complex tones, the effect of frequency on the apparent location of pure tones, estimation of the velocity of the traveling wave on the basilar membrane using judgments of lateralization, and the relative loudness of monaural and diotic sounds. While subsequent research has failed to replicate some of his findings, other findings have stood the test of time. There is no doubt that von Békésy made very substantial contributions to psychoacoustic research.

1. Introduction

In 1961 Georg von Békésy was awarded the Nobel Prize in Physiology or Medicine "for his discoveries of the physical mechanism of stimulation within the cochlea". This special issue of Hearing Research, called "Good Vibrations", honors this achievement. As will be seen from the other papers in this issue, von Békésy made substantial contributions to research in hearing in many areas, including instrumentation (including a novel audiometer whose basic design is still used today, von Békésy, 1947), middle ear mechanics, inner ear mechanics, and cochlear physiology. Although von Békésy is best known for his physiological work on hearing, he also published a substantial body of work of psychophysics, including the senses of hearing, balance, vision, touch, taste, and smell. This paper focuses on some of his work on psychoacoustics, comparing his findings and interpretations to those that have emerged since his work was published.

Georg von Békésy's published works often cover a huge range of topics within a single paper or chapter. For example, the chapter on "Auditory Thresholds" in his book "Experiments in Hearing" (von Békésy, 1960) describes, or at least mentions, absolute thresholds and how they are affected by "consumption of alcohol, the injection of cocaine, and fatiguing with intense sounds", thresholds for detecting changes in frequency and intensity, equal-loudness contours, the effect of fatiguing tones on equal-loudness contours, the effect of fatiguing tones on differential thresholds, the effect of duration on frequency discrimination, the detection of amplitude and frequency modulation, adaptation to amplitude and frequency modulation, monaural versus binaural loudness, the perception of beats, the effect of duration on loudness, Fechner's law and its empirical evaluation, thresholds for detecting changes in spatial location, and the masking of low-frequency tones by high-frequency tones and vice versa. And this list is by no means exhaustive!

A frustrating aspect of von Békésy's published work is that while he often presented circuit diagrams of the apparatus, he rarely gave details of how many subjects were used, how much training they had, and what the experimental method was; this was noted by Tonndorf (1974) who stated that "Békésy's style of writing was very terse. He rarely afforded his readers more than a glimpse of his working methods" (p. 576). This makes it hard to evaluate how reliable one should expect the results to be, and to identify reasons for some of the discrepancies that have been found between von Békésy's results and those published more recently. In what follows, I focus on aspects of von Békésy's work that have been selected because there has been a substantial body of work on those aspects in more recent years.

2. Perception of the pitch of pure tones

Having firmly established that a frequency-to-place conversion occurs within the cochlea (von Békésy, 1960), von Békésy was naturally a staunch supporter of the place theory of hearing, holding that "pitch is determined by the place of maximum excitation along the basilar membrane" (von Békésy, 1963a, p. 589). However, his physiological measurements led him to conclude that "the distribution of excitation in the human cochlea does not change with frequency for frequencies below 50 cps" (von Békésy,

Abbreviations: CF, characteristic frequency; $F0$, fundamental frequency; HRTF, head-related transfer function; ITD, interaural time difference; PTC, psychophysical tuning curve; SL, sensation level.

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1963a, p. 589), so he argued that for frequencies below 50 Hz a change in frequency is detected as a change in time pattern (note, however, that he was not entirely consistent about this, as Figure 22 in the same paper shows the place of maximum excitation moving further from the stapes as the frequency is decreased from 50 to 25 Hz). His argument that the "end of the cochlea" corresponds to a frequency of 50 Hz is consistent with recent measurements of psychophysical tuning curves (PTCs) for very low signal frequencies (Jurado et al., 2011). When the signal frequency is below 50 Hz, the tip of the PTC is shifted upwards; a masker centered above the signal frequency is more effective than a masker centered at the signal frequency. Such shifted tips suggested that the signal is being detected at a place tuned above the signal frequency. It is worth noting that the idea that the extreme apical end of the basilar membrane has a characteristic frequency (CF) of about 50 Hz is inconsistent with the commonly used Greenwood map (Greenwood, 1961, 1990), which is based on a CF of about 20 Hz at the apical end of the human basilar membrane.

One difficulty for the version of the place theory proposed by von Békésy comes from the discovery that, for a fixed frequency, the place of maximum excitation on the basilar membrane in a healthy living ear shifts toward the base of the cochlea with increasing sound level, at least for medium and high frequencies (Sellick et al., 1982; Ruggero, 1992; Zwislocki and Nguyen, 1999; Robles and Ruggero, 2001). The shift is equivalent to a change in frequency up to one-half of an octave. Forward-masking experiments support the idea that such shifts occur in humans, at least for high frequencies (Moore et al., 2002; Moore and Glasberg, 2003). If pitch were really determined by the position of the peak excitation on the basilar membrane, large shifts in pitch with level should be heard. In fact, while shifts in pitch with level do occur (Terhardt, 1974a; Verschuure and van Meeteren, 1975), they are much smaller than would be expected from the level-dependent shifts in the position of peak vibration on the basilar membrane. This led Zwislocki and Nguyen (1999) to propose a modified version of the place theory. They suggested that pitch was determined by the position of the edge of the low-frequency side of the excitation pattern on the basilar membrane; this edge changes much less in position with level than the peak.

A problem with the revised place theory of Zwislocki and Nguyen (1999) is that the pitch of a high-frequency tone is not greatly affected in the presence of a noise that would mask the low-frequency edge of the excitation pattern (this point is discussed in more detail below). A further problem for any version of the place theory is that the pitch of a tone presented to one ear can be changed by presenting a tone of the same frequency to the other ear, provided that both tones are of fairly high intensity (Thurlow, 1943). The change in pitch is in the same direction as that produced by an increase in intensity. When the same sound is presented to each ear (diotic presentation), the loudness is greater than when the sound is presented to one ear only (Moore and Glasberg, 2007); see below for more details. The pitch shift found by Thurlow may have more to do with the loudness of the tone (which depends on whether the sound is presented to one ear or both ears) than with the intensity in each ear (which determines the position of the peak excitation on the basilar membrane).

von Békésy argued that if the pitch of a pure tone is determined by the place of maximum excitation along the basilar membrane, then presenting the tone with a lowpass or highpass noise should result in a shift in pitch (von Békésy, 1963b). For example, if a 600-Hz tone is presented with a lowpass filtered noise with a cutoff frequency below 600 Hz, the summed excitation of the tone and noise should have a peak at a place on the basilar membrane with a CF below 600 Hz, so the pitch should shift downward. Similarly, a highpass noise with a cutoff frequency above 600 Hz should lead to an upward shift in pitch of the 600-Hz tone. von Békésy (1963b) reported that such pitch shifts did indeed occur, and that they could be rather large, up to about 17%. Surprisingly, the reported pitch shifts increased as the cutoff frequency of the noise was moved away from that of the tone. This is illustrated in Fig. 1. The left part shows results obtained using a lowpass noise; the pitch decrease produced by the noise is plotted as a function of upper cutoff frequency. The right part shows results obtained using a highpass noise; the pitch increase produced by the noise is plotted as a function of lower cutoff frequency. The pitch of a 600-Hz tone at 40 dB sensation level (SL) was reported to be shifted upward by 17% in the presence of a highpass noise with an SL of 30 dB and a cutoff frequency of 9600 Hz. It is hard to see how such an effect could be

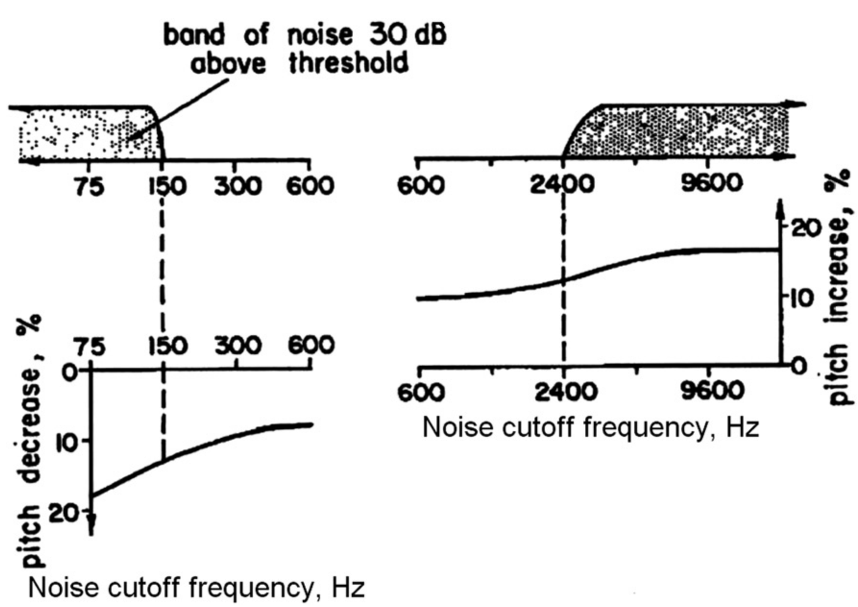

Fig. 1. Illustration of pitch shifts produced by adding a lowpass noise (left) or a highpass noise (right) to a 600-Hz pure tone, plotted as a function of the cutoff frequency of the noise. Redrawn from von Békésy (1963b).