

A HALF-CENTURY'S PERSPECTIVE ON BÉKÉSY TRACKING AND LOUDNESS GROWTH AT THRESHOLD

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Abstract

In the more than half a century since Georg von Békésy was awarded the Nobel Prize, many of his findings have stood the test of time. Implications of the width of the excursions in the Békésy tracking procedure, however, are not as simple as described in his classic book, Experiments in Hearing (von Békésy, 1960). The interpretations of his findings have created some misunderstandings in hearing science and audiology. This article reviews a large body of data on Békésy tracking and more recent threshold, discrimination, and loudness data in order to answer the following question: Is the width of the excursions a reliable indicator of cochlear pathology?

In 1947, von Békésy described a new audiometer and claimed that this new audiometer permitted the testing of recruitment. Recruitment has been defined as a rapid growth in loudness above the threshold of hearing (Fowler, 1936; Steinberg and Gardner, 1937; Brunt, 1994) and was believed to be associated with all cochlear hearing losses (Dix, Hallpike, and Hood, 1948). The audiometer was automated. As the frequency of the signal increased slowly, the subject pressed a button when the signal was audible and released it when inaudible. This pressing and releasing of the button caused the level of the signal to decrease or increase, respectively, and a visible tracing of the excursions (or trackings) between the just-audible and just-inaudible pulsed tones could be observed on recording paper that was attached to a rotating drum. This method was widely used for determining absolute threshold.

In addition to providing a measure of absolute threshold, von Békésy asserted that the width of the tracking excursions was a reliable indicator of cochlear pathology (von Békésy, 1947). His reasoning was based on the observations that cochlear hearing loss is characterized by elevated absolute thresholds and normal (or near-normal) loudness for high-level sounds. It was widely assumed that cochlear hearing loss resulted in rapid loudness growth and, accordingly, better-than-normal level discrimination. Von Békésy further assumed that the rapid loudness growth would be consistent with narrow tracking excursions and small discrimination thresholds at and near absolute threshold. Although the assumption that the width of the tracking excursions is a reliable indicator of cochlear pathology seemed reasonable at the time, there is a need to re-examine this theoretical framework with a half-century's perspective and new data.

Early experiments (1950-1975) in search of empirical support for a theoretical framework

The introduction of the Békésy audiometer sparked a flurry of debate about the clinical interpretation of the width of the tracking excursions. Von Békésy believed the width of the

excursions represented the difference limen at threshold. In fact, von Békésy (1947) claimed that his audiometric procedure was “the equivalent of the recruitment test of Fowler but had the further advantage of permitting the investigation of a single ear.” This claim was hotly debated. Despite a lack of empirical evidence showing that the difference limen was an accurate measure of recruitment, this idea persisted.

Several articles stated support of the claim that Békésy tracking is a test of recruitment. For example, Reger (1952) reported several ways in which the Békésy tracking procedure can be used, stating that recruitment testing was one of the main advantages to this testing system. Furthermore, he stated that “any child or adult capable of taking the test unknowingly tests himself for recruitment over the test frequency range”, despite a lack of published evidence. Reger and Kos (1952) examined the relationship between temporary threshold shifts and Békésy audiograms. They report that the excursions should be examined closely and demonstrate the recruitment phenomenon. In these articles, assumptions were made about recruitment without the data to support it.

There was also discussion about variables affecting the tracking procedure itself. Lüscher (1951) reported that excursions could be affected by reaction time, concentration of the patient, and fatigue. Denes and Naunton (1950) reported that there were many factors that could affect the width of the excursions, including attention, the patient’s sense of rhythm, and fatigue. [Supporting data indicating judgmental biases and criterion shifts due to the perception of a rhythmic pattern were subsequently obtained by Miśkiewicz, Buus, and Florentine (1994).] For normal listeners, the excursion widths were generally accepted to be within the 5-15 dB range (Palva, 1956; Jerger, 1960). Siegentahler (1975) examined 63 listeners with normal hearing and suggested that variability in the width of the excursion might be due to attenuation rate of the Békésy audiometer and the test frequency. In particular, the results of the study showed that using slower attenuation rates and high-frequency stimuli created smaller excursion widths and more reliable results as examined through test-retest statistical analysis using the same 63 normally hearing subjects. It is possible that any of these factors could obscure real differences between normal listeners and listeners with cochlear hearing losses. In addition to the aforementioned variables, there were reports that high-level cognitive functioning could impact the results. Harbert and Young (1968) studied 30 subjects with cochlear hearing loss and reported that the width of the excursions was influenced by the patient’s intelligence, motivation, central habituation, attention, senility, and reaction time.

Some researchers believed that the width of the excursions gave an indication of variability and adaptation. Hirsh, Palva, and Goodman (1954) reported that von Békésy was actually measuring the variability about the absolute threshold and not the difference limen. Tsuiki (1966) suggested that the narrowing of the excursions was due to rapid adaptation and not recruitment. Later, Harbert and Young (1964; 1968) examined several Békésy tracings from ears with different pathologies and agreed that abnormal adaptation is the cause of the narrowing of the excursions. Whatever was being measured, by the end of the 1970s it was clear that the width of tracings, as described by von Békésy (1947), was not a good predictor of general cochlear pathology. It was clear that some of the assumptions needed to be reexamined by addressing the following questions.

Is level discrimination better for listeners with cochlear pathology than normal listeners?

The difference limen (DL) for level (aka, intensity DL or JND) is the just-noticeable difference between two audible stimuli and, accordingly, is measured at supra-threshold levels. It has been measured using different experimental paradigms (e.g., two-tone comparison and amplitude modulation). One problem with using an amplitude-modulation paradigm is that the data are strongly frequency dependent for normal listeners. [For review, see Buus *et al.* (1982a,b) and

Turner *et al.* (1989).] The two-tone comparison procedure yields little frequency dependence (Jesteadt *et al.*, 1977), except above 4 kHz (Florentine 1983; Florentine *et al.*, 1987). Several studies (Hirsh *et al.*, 1954; Jerger and Jerger, 1967; Florentine *et al.*, 1979; 1993; Turner *et al.*, 1989) measured the level DLs using two-tone comparison and concluded that there was little to distinguish between recruiting, non-recruiting, and normal listeners. Only Denes and Naunton (1950) reported that the DL for level increases or remains constant for recruiting ears. In the most comprehensive study of level DLs as a function of level in listeners with sensorineural hearing loss, Florentine, Reed, Rabinowitz, Braida, Durlach, and Buus (1993) showed that different audiometric configurations result in different DL functions for level. Although it was not possible to be certain of the etiology of hearing loss, some etiologies have been associated with specific audiometric configurations of hearing loss. Their results also indicate that there are large individual differences among listeners with sensorineural hearing losses and that the level DLs are not smaller than normal, except perhaps in the case of rising audiograms. The available data, therefore, are overwhelmingly inconsistent with a correlation between recruitment and smaller-than-normal DLs for level in cochlear pathology.

Is loudness at threshold the same for cochlear pathology and normal hearing?

One common assumption was that loudness at threshold was zero and, accordingly, it was displayed as zero in published figures. This assumption was never tested because it was commonly assumed that loudness below 4 dB SL could not be measured due to limitations of the available psychophysical procedures. Advancements in an innovative experimental paradigm by Buus, Müsch, and Florentine (1998) led to a new understanding of loudness at threshold. [For review, see Florentine (2009) and Florentine, Popper, and Fay, 2011].] Their measurements showed a low, but positive value of loudness at threshold. This finding is now widely accepted and it has been incorporated into the new ANSI S3.4-2007 loudness standard.

The collapse of the assumption that loudness at threshold was zero opened other assumptions to scrutiny. If loudness at threshold is truly greater than zero, it may have a value that differs among individuals. It is possible that damage to the cochlea causing hearing loss may also affect loudness perception, especially at the threshold of hearing. Buus and Florentine (2002) actually measured loudness at threshold and found that some listeners with cochlear hearing losses have abnormally elevated loudness at threshold, which is called softness imperception. Although Moore (2004) reported results that appear inconsistent with the concept of softness imperception, he only tested four listeners with one procedure. Because equal-loudness measurements are fraught with problems at low SLs (Hellman and Zwislocki, 1961), it is desirable to obtain loudness measurements using a variety of converging methods. For this reason, Florentine, Buus, and Rosenberg (2005) measured reaction times (RTs) for 200-ms tones at different frequencies. Because equal simple RTs for tones have been shown to correspond closely to equal loudness and because measurements of RTs are possible even when tones are set at threshold (for review, see Wagner *et al.*, 2004; Epstein, 2011), RTs were used to indirectly assess loudness at threshold. Results for six listeners with cochlear hearing losses consistently showed faster RTs to tones at and near threshold for a frequency with elevated threshold than for a frequency with normal or near-normal threshold. This evidence supports the idea that some listeners with cochlear hearing losses have greater-than-normal loudness at threshold. Florentine, Mumby, and Cleveland (2004) further tested this concept with 22 listeners with cochlear hearing losses and the results suggest the existence of softness imperception. The majority of the data indicate that loudness at threshold has a positive value and that loudness can be greater than normal in some listeners with hearing losses of primarily cochlear origin, and that differences in test frequency do not account for this effect (Epstein and Florentine, 2006).

Is the rate of loudness growth faster in cochlear hearing losses than normal hearing?

Hellman and Zwislocki (1961) provided compelling data that loudness near threshold had an average slope of about unity or slightly larger for listeners with normal hearing. According to a summary figure from Buus and colleagues (1998) published decades later, Hellman and Zwislocki's finding was supported by a number of studies that measured the loudness of low-level tones using a variety of methods.

Although it had been assumed that cochlear pathology leads to an abnormally rapid growth of loudness immediately above an elevated threshold, this assumption is not supported by empirical data. The rate of loudness growth with increasing level at and near threshold for listeners with sensorineural hearing losses is not radically different from listeners with normal hearing (Hellman and Zwislocki, 1964; Hellman, 1997, 1999; Buus and Florentine, 2002; Moore, 2004; Smeds and Leijon, 2011).

Current View

The previous sections of this article show that none of the three assumptions have stood up to empirical testing. Level discrimination is not generally better for listeners with cochlear pathology than listeners with normal hearing, and can often be worse. Loudness at threshold is highly likely to be different for cochlear pathology than for listeners with normal hearing. The rate of loudness growth with increasing level near threshold is usually not much greater for cochlear hearing loss than for normal hearing. It should be noted that these are general comments based on group data, and that there are large individual differences in auditory processing among listeners with hearing losses that have been considered to be of predominantly cochlear origin. It is becoming increasingly clear that not all listeners with cochlear hearing losses have the same abnormal loudness growth. When data for listeners with hearing losses are averaged, important individual differences are averaged out, as pointed out by Marozeau and Florentine (2007). In fact, Marozeau and Florentine (2007) examined data from past studies to test two loudness-growth theories: softness imperception and recruitment. Five different studies using different methods to obtain individual loudness functions were used: absolute magnitude estimation, cross-modality matching with string length, categorical loudness scaling, loudness functions derived from binaural loudness summation, and loudness functions derived from spectral summation of loudness. Results showed large individual differences. Some of the individuals demonstrated softness imperception, others showed recruitment, and there were some who did not fit into either group yet showed abnormal loudness growth. This research indicates that there is large individual difference and one method of determining loudness growth or one loudness growth theory does not account for all hearing losses of primarily cochlear origin.

Conclusion

Von Békésy's (1947) audiometer was a very innovative apparatus for measuring auditory thresholds. There is no evidence, however, of its ability to determine the presence of recruitment and cochlear pathology. The claim that his audiometer was "...the equivalent of the recruitment test of Fowler but has the further advantage of permitting the investigation of a single ear" has not stood the test of empirical inquiry. Although von Békésy was incorrect in his assumptions about recruitment and determining loudness growth at threshold, his theoretical work provided a basis for empirical research, which has led us to our current understanding of loudness growth functions.

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