Scientific Legacy of Professor Andrzej Rakowski in Current Studies of Pitch Discrimination in Music

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Abstract

This paper is an overview of experimental studies of pitch discrimination and pitch strength in music conducted in recent years at the Chopin University of Music. The studies were inspired by Professor Andrzej Rakowski's findings and ideas on the foundations of pitch perception in music. The measurements of pitch discrimination show that the ability to hear pitch differences markedly decreases below 200-Hz frequency so that the pitch discrimination threshold increases to about a semitone at very low frequencies. The auditory system's relatively poor ability of pitch discrimination of low-frequency tones also manifests itself in much less accurate identification of musical intervals and melodic patterns in the lowest octaves of the musical scale, comparing with higher octaves. The paper also discusses the results of an experiment which indicate that some percussion instruments of the indefinite pitch family produce a sensation of pitch strength comparable with melodic instruments.

Keywords: pitch discrimination, pitch strength, musical intervals, melody identification in music

1. Introduction

During his impressive scientific career, which lasted for six decades, a substantial part of Professor Andrzej Rakowski's work was focused on pitch perception, an area in which his accomplishments were most remarkable. In his studies of pitch perception he investigated, among others, various phenomena concerned with pitch discrimination. His first notable achievement in that field, reported at the ICA Congress in Budapest, was the finding that the difference limen for pitch (pitch DL) of a 1-kHz tone, measured in extensively trained musician subjects, might be as low as 0.35 cents, which corresponds to nearly 1/300 of a semitone [1]. This finding was received with some disbelief at the congress as the lowest pitch DLs, known at that time, *e.g.*, [2], were about three times larger. The experiment reported in Budapest began Professor Rakowski's extensive explorations of pitch discrimination, focused on two main problems: (1) he measured pitch DLs of pure tones to estimate the limits of the auditory system's frequency resolution and (2) he sought to determine how accurately are discerned the pitches of musical tones.

Professor Rakowski's investigations of pure-tone pitch discrimination have deepened the understanding of the frequency discrimination and frequency coding processes in the auditory system. In his studies conducted with the use of recorded samples of musical tones he has given detailed evidence for an effect known in musical praxis, that the pitches of tones played on different instruments or in different registers of an instrument are heard with different accuracy. Rakowski [3] introduced a novel concept of *pitch strength* referred to the accuracy or salience of the pitch sensation.

This paper gives an overview of research on pitch discrimination and pitch strength in music conducted in recent years by Professor Andrzej Rakowski's associates at the Chair of Musical Acoustics, Chopin University of Music. Special attention is given in the overview to the perception of low-frequency tones. The investigations discussed here were inspired by Professor Rakowski's studies of pitch perception and were carried out to pursue his scientific ideas further, within the current research areas in psychoacoustics.

2. Pitch discrimination of low-frequency tones

Pitch DL, a measure of auditory sensitivity to pitch changes and frequency-discrimination ability of the auditory system has been typically defined as the just detectable change in frequency, ΔF, between two successive tone pulses. Reported data have shown that ΔF increases with tone frequency and amounts to about 1 Hz at a 500-Hz frequency, 3 Hz at 1 kHz and 15 Hz at an 8-kHz frequency [4].

Pitch discrimination of low-frequency tones, in a range below 200 Hz, has been to a much lesser degree explored than the discrimination of higher-pitched tones. It should be noted here that the audio frequency range below 200 Hz encompasses about 40% of the musical pitch scale, down from note G3. In psychoacoustics, the ability to detect a change in a tone's frequency is usually specified as ΔF, in hertz, or as a percentage of a reference frequency. In studies related to music pitch DLs are also expressed as the just detectable pitch interval, in cents. A few studies conducted with the use of very low pitched tones have shown that pitch DL, in cents, substantially increases with decreasing tone frequency below 200 Hz [1, 2, 4] and amounts to nearly a semitone at 25 Hz [5].

Published pitch DLs for frequencies below 100 Hz are sparse and show considerable variability across experiments and subjects. In a recent, more systematic study of pitch discrimination of low frequency pure tones Rogowski and Miśkiewicz [6] measured pitch DLs at six frequencies from 20 to 100 Hz and at two higher frequencies – 250 Hz and 1000 Hz. The filled symbols in Fig. 1 show the pitch DLs, in cents, averaged across six subjects. For comparison, Fig. 1 also shows pitch DLs determined in other studies, by an adaptive, up-down adaptive 2AFC method and by the method of adjustment.

The data from 2AFC experiments (Fig. 1) show that pitch DL substantially increases with decreasing tone frequency below 100 Hz and amounts to as much as 270 cents at 20 Hz [6]. It is also apparent that pitch DLs determined by adjustment are much lower than those measured in a 2AFC task. The difference in the size of pitch DL determined by different methods has long been known in the literature. Wier *et al.* [7] reported that the pitch DL estimated for a 1-kHz pure tone by an adaptive, 2AFC procedure, 70.7% correct, is by a factor of 1.6 larger than the DL from the adjustment procedure. This difference is a partial explanation for the very low pitch DLs obtained by Rakowski [1]. Another factor that contributed to a pronounced decrease of the pitch DL estimated is his experiment was the use of correct-answer feedback. The data replotted in Fig. 1 from Jaroszewski [8] indicate that pitch DLs measured by the adjustment method, with and without feedback, differ by a factor of 2 to 4 at various frequencies.

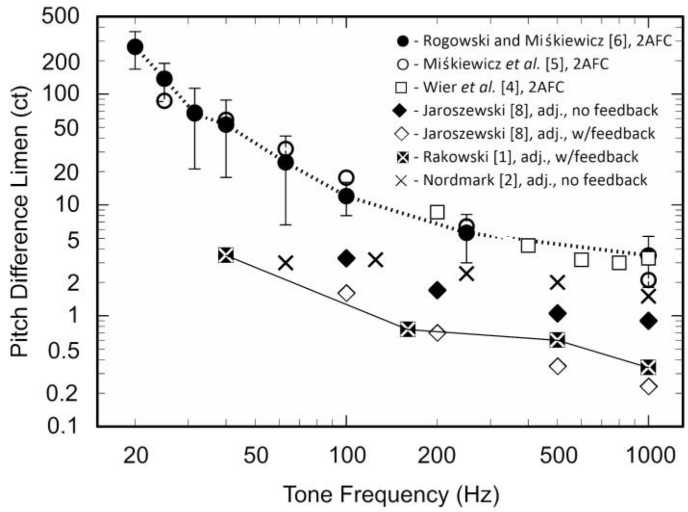

Figure 1. Pitch DLs, in cents, in a 20–1000 Hz frequency range. The data show the 70.7% correct point estimated by an adaptive, 2AFC procedure [4-6], the DLs determined by an adjustment procedure with no feedback [2, 8], and by adjustment with feedback [1, 8]

The method of adjustment involves various judgmental variables which are very difficult to control. One such a variable is the cue used by the subject for comparing the two tones during the adjustment task. Although it is assumed that the subject evaluates the identity of two tones by comparing their pitches, he/she may also, consciously or unconsciously, use other cues. For example, the judgment of identity might possibly be aided by the sensation of roughness, which is strongly pronounced at low frequencies.

To determine whether the pitch DL measured for low-frequency pure tones differs when the subject's task is to indicate which tone has a higher pitch and when the subject has to evaluate whether two tones are identical we shall present the results of an experiment conducted by Wolski [9] with the use of a procedure modelled after Sęk and Moore [10]. Pitch DLs were measured in two stimulus paradigms. In the first, two tone pulses were presented in each trial and the subjects were asked to indicate which pulse had a higher pitch. The discrimination threshold determined in such a way has been termed the *difference limen for frequency*, *DLF*, by Sęk and Moore [10]. In the second paradigm two successive pairs of tone pulses were presented; in one pair the tone frequencies were identical and in the other one different. The subjects were required to indicate in which pair the tone pulses were different. The threshold measured in such a paradigm has been called the *difference limen for change, DLC* [10]. In both conditions thresholds were estimated at the 79.4% correct point, by an up-down, adaptive, 2I, 2AFC procedure with feedback. Figure 2 shows the DLFs and DLCs averaged across four subjects [9], the DLFs and DLCs reported by Sęk and Moore [10] and the group DLFs determined by Rogowski and Miśkiewicz [6], replotted from Fig. 1. Open diamonds show the results of the best subject in the experiment of Rogowski and Miśkiewicz [6].

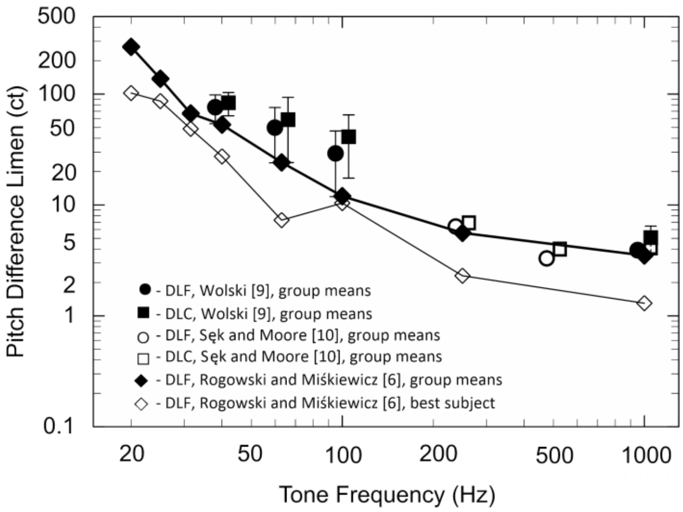

Figure 2. Difference limens for frequency (DLF) and difference limens for change (DLC) measured for pure tones in various experiments, in a frequency range of 20–1000 Hz. For clarity of presentation the symbols indicating the DLF and DLC values are slightly shifted to the left and to the right along the abscissa. The error bars show the standard deviation of individual means around the group mean in Wolski's [9] experiment

The results plotted in Fig. 2 show that DLFs and DLCs are similar to one another at very low frequencies. This finding indicates that the possibility of using auditory cues other than pitch for the judgment of perceptual identity of two tones does not improve the result of frequency discrimination measurement over the level obtained when the subject is required to detect the direction of the pitch change caused by a difference in frequency between two tones. It also should be noted that the data collected by Wolski [9] are in agreement with those of Sęk and Moore [9] who reported that DLFs and DLCs did not differ one from another at frequencies up to 2 kHz whereas at 4 kHz and higher frequencies DLFs were markedly larger than DLCs.

At this point, let us go back to Rakowski's experiment [1] which was the starting point for our discussion. It seems to be clear that the low pitch DLs obtained in his study resulted, at least in part, from using the method of adjustment with feedback. Apart from this, it should be noted that the pitch DLs measured in later experiments in Professor Rakowski's laboratory were very often lower than those obtained by other researchers with the use of the same methods. An explanation for this effect is Professor Rakowski's special approach to the measurements of pitch discrimination.

Depending on the purpose of the experiment, Rakowski's measurements of pitch discrimination were either subject-oriented or object-oriented experiments, *cf.* [11]. An experiment was subject-oriented when it was conducted to study the physiological limits of the auditory system's frequency resolution. When the measurements were made to determine how accurately are discerned the tone pitches in music, the experiment was object-oriented and the subject served in that case the role of a human instrument for pitch measurement. Professor Rakowski gave much weight to the selection and training of his human measuring instruments. His investigations of pitch perception were usually conducted on musicians who underwent extensive training prior to the participation in the experiment. Sometimes Professor Rakowski managed to fish out an unbelievably gifted person for pitch discrimination from the student population at the Chopin University of Music.

An example from our recent study [6], of a subject with particularly good abilities for pitch discrimination, is shown in Fig. 2. The pitch DL of that subject, measured as the 70.7% correct point, is 2-3 times smaller at a 1-kHz frequency than in other experiments conducted on trained subjects with the use of a similar method. It is also apparent that the pitch DLs of the best subject are lower at frequencies below 1000 Hz.

3. Pitch strength of low-frequency tones in music

In a paper introducing the concept of pitch strength Rakowski [3] suggested that the measure of pitch strength be derived from the dispersion of multiple adjustments of the pitch of a pure tone to the pitch of the tone under investigation. Although other authors [12] opted for alternative methods of pitch strength assessment, Professor Rakowski strongly advocated the adjustment method and argued that it reflected, to a considerable extent, the conditions of pitch intonation in music. An unquestionable advantage of that method is that it provides both an estimate of pitch strength, inferred from the standard deviation of pitch adjustments of the test tone, and an estimate of the sound's pitch level, taken as the mean of adjustments. Such a method is also very useful for identifying individual pitch levels when a sound is perceived as having more than one pitch.

The measurements of pitch DL, discussed in Section 2, have shown that the pitches of low frequency tones are heard less accurately than at higher frequencies. From a perspective of music perception it is important to determine whether the poorer ability of discerning pitch changes of individual, low-frequency tones is manifested by less accurate identification of musical intervals and melodies in low pitch registers?

The influence of the pitch strength on musical interval identification accuracy was studied in an experiment conducted on a group of musicians by Rogala *et al.* [13]. The sound stimuli were pure-tone dyads constituting 13 intervals, from unison to octave. Pitch strength was controlled by presenting the dyads in different octaves and by varying their duration. Figure 3 shows the percentage of correct identifications of the intervals, as a function of tone duration, for dyads presented in the second octave (65.4–130.8 Hz), the fourth octave (261.6–523.3 Hz) and in the sixth octave (1047–2093 Hz). The data plotted in Fig. 3 show two effects: (1) due to the splatter of the sound spectrum, interval identification worsens when a brief dyad is shortened and the pitches of the tones are heard less accurately, (2) interval identification is much worse in the lowest octave due to poor frequency discrimination ability of the auditory system at low frequencies.

In an earlier study Rogala [14] used a method of pitch strength assessment that reflected, to a very large extent, the conditions of pitch perception in music. The stimuli were short melodies, made up of electronically transposed musical instrument sound samples presented in a sequence, in random order. The transposition enabled to produce

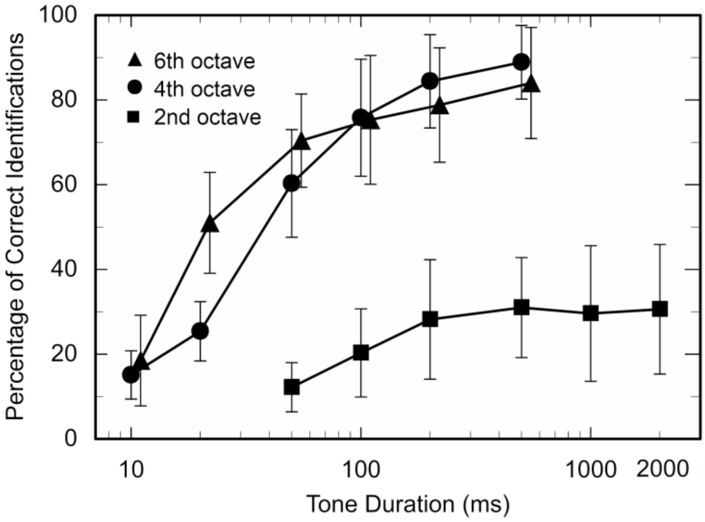

Figure 3. Percentage of correct identifications of musical intervals, as a function of duration of a pure-tone dyad, in different octaves of the musical scale. The error bars show the standard deviation of 14 individual means around the group mean. Data from [13]

melodic patterns from samples of non-melodic percussion instruments which make only one sound and are not pitched to any specific note in music. The stimuli also included melodies produced from sound samples of string instruments, woodwinds, brass instruments, and melodic percussion instruments. The subjects were asked to write down each melody presented in a series of trials.

Figure 4 shows the group mean percentage of correctly written down melodies for each instrument. The instruments are ordered along the abscissa according to ascending pitch of the original sound sample used for making a melody. The last two instruments – the bass drum and the triangle – belong to the class of indefinite pitch instruments. The data shown in Fig. 4 indicate that melodies made up of low-pitched tones, in the first and in the second octave, were identified less accurately than those in higher octaves. A noteworthy effect is that the melodies made up of a transposed sample of the triangle, an indefinite pitch instrument, yielded an identification score comparable to low-pitched tones of melodic instruments.

4. Final remarks

The studies discussed in this paper have demonstrated that the ability of discerning pitch changes of pure tones substantially worsens with decreasing frequency, below about 200 Hz. The poorer ability of pitch discrimination of low-frequency tones causes the musical intervals and melodies to be identified less accurately in the lowest octaves of the musical scale than in higher octaves. However, one may have serious doubts as to whether the pitch DLs measured for pure tones reliably reflect the accuracy of pitch perception of musical instrument tones at low frequencies?

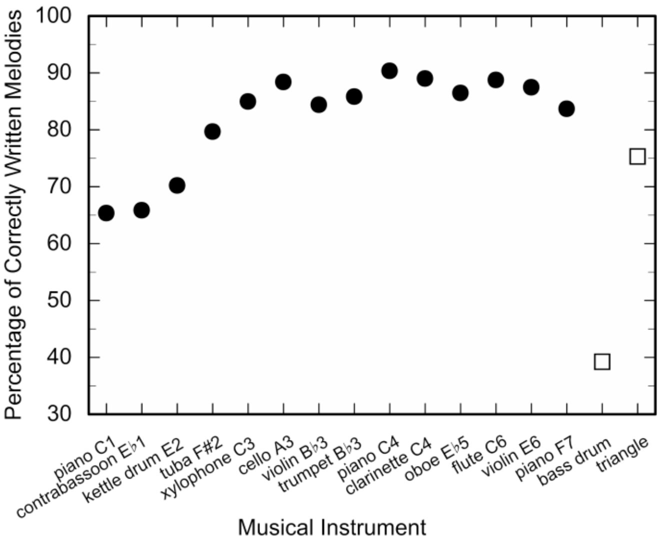

Figure 4. Group percentage of correctly written down melodies, made up of electronically transposed sound samples of various musical instruments. The instruments are ordered on the abscissa according to ascending pitch of the sample. Data replotted from Rogala [14]

It may seem that pitch DLs, to be representative of pitch discerning ability in music, should be measured with harmonic complex tones or with musical instrument samples, however, the use of such stimuli would be burdened with very difficult methodological problems. When tones with harmonic spectra are used in a psychophysical procedure of pitch DL measurement at very low frequencies it is easy to indicate which of the tones has a higher pitch in a trial by listening to the pitches of the higher partials, rather than to the low pitches, or nominal pitches of the tones. The auditory threshold curve and the equal-loudness curves are very steep in the low-frequency range therefore the higher partials of low-pitched musical tones are very much highlighted and easy to hear out.

Professor Rakowski paid very much attention to the relevance of his laboratory experiments to the sound perception conditions encountered in music, and distinguished absolute pitch DLs from operational DLs. Absolute pitch DL is the smallest frequency difference that a subject can discern in laboratory conditions. Operational pitch DL is a pitch difference threshold estimated in conditions relevant to the perceptual context meant to be studied in the experiment, for example, to music listening [15].

Professor Rakowski took a broad, cognitive perspective in his research on pitch perception and put forward a theory in which pitch was considered a multidimesional perceived attribute of sound, serving the role of a communication code in music. In today’s terms we would call him a precursor of cognitive and ecological psychoacoustics in the scientific study of sound perception in music. The peak of his research activity fell on the period when explorations of pitch perception were focused mainly on purely sensory and methodological issues. Most studies of pitch perception were conducted with the use of pure tones and static complex tones at that time and an attempt to bring an experiment closer to real life conditions was always a big challenge. The present, digital sound processing technology and computer-controlled procedures have removed most of those impediments. It also should be noted that much insight into the processes of pitch perception in music is now obtained from brain imaging studies in cognitive neuroscience. In the context of current advancements in auditory research Professor Andrzej Rakowski's scientific legacy is gaining a new perspective.

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