

Pitch Strength of Residual Sounds Estimated Through Chroma Recognition by Absolute-Pitch Possessors

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Absolute pitch is a unique feature of the auditory memory which makes it possible for its possessors to recognize the musical name (chroma) of a tone. Six musicians with absolute pitch, selected from a group of 250 music students as best scoring in musical pitch-naming tests, identified the chroma of residue pitch produced by harmonic complex tones with several lower partials removed (residual sounds). The data show that the percentage of correct chroma recognitions decreases as the lowest physically existent harmonic in the spectrum is moved higher. According to our underlying hypothesis the percentage of correct chroma recognitions corresponds to the pitch strength of the investigated tones. The present results are compared with pitch strength values derived in an experiment reported by HOUTSMA and SMURZYNSKI (1990) for tones same as those used in this study but investigated with the use of a different method which consisted in identification of musical intervals between two successive tones. For sounds comprising only harmonics of very high order the new method yields a very low pitch recognition level of about 20% while identification of musical intervals remains stable at a level of about 60%.

Keywords: absolute pitch, residual sounds, virtual pitch.

1. Introduction

Listeners who participate in psychoacoustic experiments are usually selected on the basis of an audiometric screening test and do not have to possess any unique hearing abilities. However, in certain kinds of experiments, intended to examine the characteristics of auditory perception, listeners may be required to possess specific musical listening skills, for example, the ability to identify musical intervals (HOUTSMA and GOLDSTEIN, 1971; HOUTSMA and SMURZYNSKI, 1990; HOUTSMA, 2007; HSIEH and SABERI, 2007). Such an ability was essential in an experiment of HOUTSMA and SMURZYNSKI (1990) sought to examine the effect of the strength of residue pitch on identification of musical intervals. Residue pitch

is a sensation of pitch corresponding to the fundamental frequency of a harmonic complex tone perceived while the fundamental tone, as well as several other lower harmonics that the ear is capable to resolve, are physically absent (SCHOUTEN, 1940; SCHOUTEN *et al.*, 1962). The strength of residue pitch is the saliency or distinctness of the residue pitch sensation. Assuming that decreasing pitch strength manifests itself in poorer identification of musical intervals produced with the tones investigated, HOUTSMA and SMURZYNSKI (1990) took the percentage of correct identifications of intervals as a measure of the strength of residue pitch.

Experiments described in the present study make use of another musical property of hearing, called absolute pitch. Absolute pitch is the ability to identify the pitch chroma or the musical name of a tone without the use of a reference pitch (MIYAZAKI, 2007). In Western culture absolute pitch prevails in only several percent of musicians' population (DEUTSCH *et al.*, 2006). Musicians who possess absolute pitch are able to assign the pitches of tones across the musical scale to 12 within-octave categories, known as pitch chromas (BACHEM, 1937; RAKOWSKI and MIYAZAKI, 2007).

In the present study it was assumed that listeners with absolute pitch perfectly identify the pitch chromas of tones with high pitch strength; as the pitch strength decreases, identification of pitch chroma becomes poorer, so that for tones of very low pitch strength the percentage of correct identification responses would drop to 8.3%, a value corresponding to random identification of 12 pitch categories. According to our hypothesis the percentage of correct chroma identifications made by listeners with absolute pitch may be taken as a measure of the pitch strength. The present study was carried out to verify the above assumption in an experiment consisting in identification of the chromas of residual pitches produced by harmonic complex tones. The experiment was intended to reexamine the findings reported by HOUTSMA and SMURZYNSKI (1990) who assessed pitch strength by identification of musical intervals produced by two successive tones. To obtain data for comparison, the present experiment replicated to the possible extent the stimuli and conditions of stimuli presentation used by HOUTSMA and SMURZYNSKI (1990).

2. Method

2.1. Selection of listeners

The listeners who took part in the experiment were six musicians with absolute pitch selected in a previous pitch-naming test carried out on 250 students of The Fryderyk Chopin University of Music (RAKOWSKI *et al.*, 2008; MAKOMASKA and RAKOWSKI, 2008; MAKOMASKA, 2008). The test comprised 25 piano sounds with pitches quasi-randomly selected from a range of five octaves, from C2 to B6. Each musical pitch category (chroma) was presented at least twice in the test, in different octaves. The test was played back to the listeners in two

versions, with a 6-s and 2-s time interval between the onsets of successive tones. During that interval the listener had to write down the pitch name of the tone on an answer sheet. The tests were presented through loudspeakers at a loudness level of about 75 phons, to groups of listeners not exceeding 15 persons. Twelve students who achieved at least 96% of correct answers, i.e., made not more than one error in each of the two tests, participated in additional pitch-naming tests conducted with the use of pure tones and synthetic complex harmonic tones. Six students who achieved best scores in those tests were chosen to participate as subjects in the experiments reported in this paper.

2.2. Apparatus and stimuli

A personal computer, equipped with a 16-bit CMI19761A digital-to-analog converter, was used to generate the signals and record the listeners' responses. Signals were presented binaurally through Beyerdynamic DT 990 PRO headphones with circumaural ear cushions.

The stimuli were modeled after those used by HOUTSMA and SMURZYNSKI (1990). Figure 1 shows schematically the stimulus spectrum. As seen in Fig. 1, the stimuli were harmonic complex tones consisting of M consecutive components of equal amplitude and with the lowest physically present component being the N -th harmonic of the missing fundamental. The difference between the stimuli in the present and in the earlier study is that HOUTSMA and SMURZYNSKI (1990) used pairs of successive tones for identification of musical intervals whereas in the experiment reported here the listeners were asked to identify directly the musical pitches of single tones.

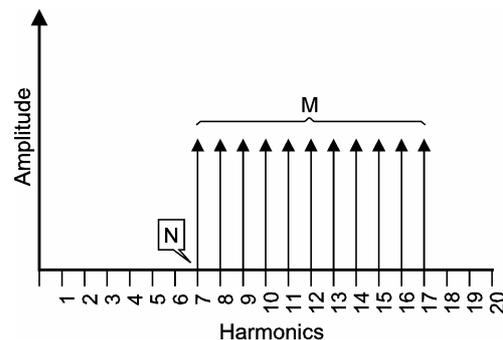


Fig. 1. Example spectrum of a residual tone comprising $M = 11$ successive harmonics, with lowest harmonic $N = 7$.

The present study comprised two experiments. In both of them the frequencies of the missing fundamental corresponded to the frequencies of eight musical pitches: G, G#3, A3, A#3, B3, C4, C#4, D4 (196.0, 207.7, 220.0, 233.1, 246.9, 261.6, 277.2 and 293.7 Hz). The set of eight pitches was chosen with reference to the musical intervals used in HOUTSMA and SMURZYNSKI'S (1990) study. In

their experiment, the frequency of the missing fundamental of the first tone in a pair was 200 Hz. The frequency of the second tone was one of those that were formed by seven melodic intervals between a minor second and a perfect fifth, in upward direction from the first tone. In the present study, the tone frequencies used by HOUTSMA and SMURZYNSKI (1990) were slightly shifted to adjust them to the standard musical tuning, based on a reference pitch of $A4 = 440$ Hz, so that the frequency of the lowest virtual fundamental tone was 196 Hz (G3) rather than 200 Hz. The missing fundamental frequencies of all stimuli were therefore by 35 cents lower than in HOUTSMA and SMURZYNSKI's (1990) study.

In Experiment I, pitch judgments were made for five conditions with lowest harmonic number $N = 7, 10, 13, 16$ and 19 . To explore in more detail the effects examined in Experiment I, an additional experiment, labeled Experiment Ia, was carried out with the use of complex tones consisting $M = 11$ harmonics, with lowest harmonic numbers $N = 11, 12, 14,$ and 15 . In Experiment II the lowest harmonic number, N , was either 10 or 16 and the number of harmonics, M , was $2, 3, 5, 7$ and 11 .

HOUTSMA and SMURZYNSKI (1990) randomized the lowest harmonic number N in sets of trials. The purpose of randomization was to reduce the possibility of identifying an interval by listening to the pitch shift of an individual harmonic instead of listening to the interval formed by the residue pitches. Due to randomization, the actual lowest harmonic number could differ by ± 1 from the nominal N value in their study. A test block for each data-point consisted of 63 test tasks (9 combinations of 3 N -value in pair of tones forming melodic interval $\times 7$ melodic intervals). Each block has been assigned a mean value of N number, denoted as \bar{N} (mean value of N in block). Procedure described above lowered the resolution of interval identification method. The adjacent data-points \bar{N} differed by 3. Such a randomization was not necessary in the present study as the listeners' task consisted in identification of the pitch chroma of a single tone, not in recognizing a musical interval produced by two successive pitches.

Both in previous and in present study to mask aural combination tones and avoid their possible influence on the judgments of residue pitch, the stimuli were presented against a constant background of pink noise set at 30 dB SL. The stimuli levels were set 20 dB above masked threshold. All tones were 512 ms in duration, including a 40-ms linear rise and fall.

In the present study a test block comprised 40 trials (8 pitches \times 5 spectral conditions) in Experiment I, 32 trials (8 pitches \times 4 spectral conditions) in Experiment Ia and 80 trials (8 pitches \times 10 spectral conditions) in Experiment II. In each test block the stimuli were presented in random order.

2.3. Procedure of chroma recognition

In all experiments the listeners' task was to identify the tone's pitch chroma, i.e., its musical name. The experimental procedure was based on a one-interval

stimulus presentation paradigm with a 12-alternative forced-choice answer pattern. The listener was seated in front of a computer monitor. A piano keyboard, comprising 12 keys, from C to B, was displayed on the monitor screen. After listening to a tone the listener indicated its pitch by touching a virtual key on the monitor. The next tone was presented 1 s after entering the response. Unlike in HOUTSMA and SMURZYNSKI'S (1990) experiment, the listeners were not given correct-answer feedback. Each listener completed 26 test sequences. The first sequence was a practice task and was discarded in the calculations of results.

Both experiments were preceded by training sessions. During training sessions the listeners performed the same tasks as in the main experiment, but were given feedback indicating the correct identifications. At the end of each training session the percentage of correct responses was displayed on the screen. Training sessions were repeated until the percentage of correct responses reached a stable level and further tests did not improve the listener's performance. Each listener completed at least five training sessions.

During training sessions, listeners reported that in some tones they were hearing simultaneously more than one pitch. They were instructed to identify the lowest pitch.

3. Results

Group results of Experiment I are plotted in Fig. 2. The abscissa shows the lowest harmonic's number in a complex tone (N). The ordinate is the percentage of correct pitch chroma identifications. Closed symbols indicate group means obtained for five listeners. Open symbols show the results of musical interval identification reported by HOUTSMA and SMURZYNSKI (1990). It should be noted that HOUTSMA and SMURZYNSKI'S data are related to averaged N values (\bar{N}) due to randomization used in interval identification procedure.

Both sets of data shown in Fig. 2 demonstrate a similar, general tendency: the pitch strength decreases as the lowest physically existent harmonic of a complex tone is moved higher. In the present data the pitch strength of tones with lowest harmonics of $N = 7$ and $N = 10$ is about the same. A substantial decrease in pitch strength starts from $N = 13$ and for $N = 19$ and reaches a value of less than 20%, not far from random guessing (8.3%). In HOUTSMA and SMURZYNSKI'S (1990) experiment the decrease of identification with raising N is smaller and reaches a plateau of about 60% for $\bar{N} \geq 13$.

Figure 3 shows individual results of five listeners. In all but one cases individual results are in close agreement with the group means shown in Fig. 2 and the percentage of correct pitch identification abruptly decreases when the lowest harmonic is raised from for $N = 16$ to $N = 19$. Results of listener JN demonstrate a somewhat different tendency as his percentage of correct responses does not appreciably change between $N = 16$ and $N = 19$. The pattern of data obtained

for listener JN is similar to that seen in Fig. 2, in HOUTSMA and SMURZYNSKI'S results (open circles).

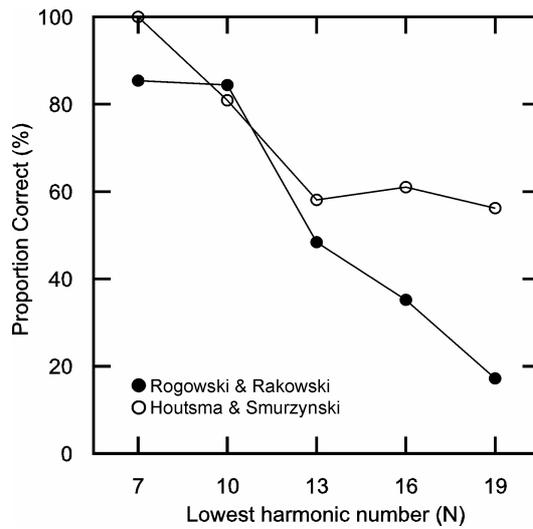


Fig. 2. Percentage of correct chroma recognitions as a function of the lowest harmonic number. Closed circles show the results averaged across five listeners in Experiment I. Open circles are data reported by HOUTSMA and SMURZYNSKI (1990) for recognition of melodic intervals.

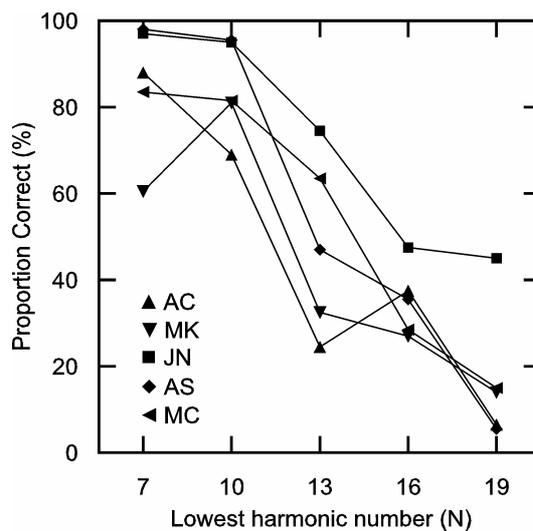


Fig. 3. Percentage of correct chroma recognitions as a function of the lowest harmonic number. Individual results obtained in Experiment I for five listeners.

To further explore the possible causes of a large, stepwise drop in pitch strength observed when N is raised from 13 to 16 an additional experiment,

called Experiment Ia, was conducted with the use of complex tones with lowest harmonic numbers, N , of 11, 12, 14 and 15.

Results of Experiments I and Ia are combined in Fig. 4. Open symbols connected by dotted lines show individual data and the group means are represented by closed symbols connected by solid line. Results shown in Fig. 4 indicate that the transition from a range of good chroma identification to poor identification is more abrupt than it could be inferred from the relatively sparse data points in Experiment I. An abrupt drop in the percentage of correct responses is seen for $N = 13$, for three listeners and for $N = 12$ and 14, for the two other ones. For $N = 16$ the percentage of correct responses somewhat increases, in comparison with adjacent data points ($N = 15$ and 19). A similar local maximum is seen in Fig. 2, in HOUTSMA and SMURZYNSKI'S (1990) results (open symbols).

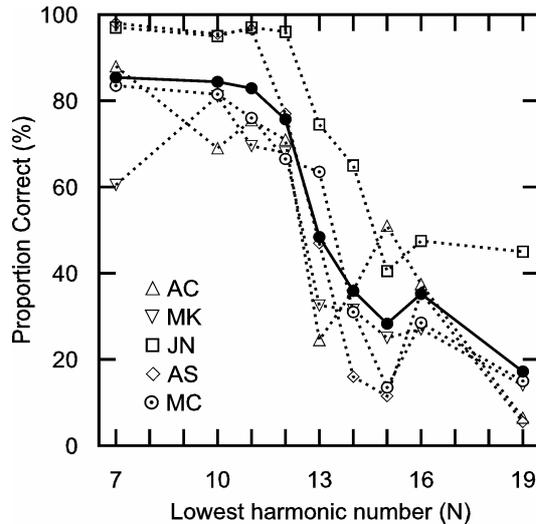


Fig. 4. Combined results of Experiments I and Ia. Percentage of correct chroma recognitions as a function of the lowest harmonic number. Open symbols – individual data, closed circles group means for five listeners.

Table 1 shows the distribution of chroma identifications. The data are combined results obtained in Experiments I and Ia. In row "0" shown is the number of correct pitch identifications for each N number (i.e. chroma indications of nominal value). In the remaining rows given are numbers of wrong identifications specified as an upward or downward pitch departure in semitones from the nominal chroma. The data in Table 1 show that the distribution of answers is asymmetrical around the nominal pitch chroma. For $N = 14, 15$ and 16 the pitches given by the listeners are in most cases lower than the nominal pitch chroma. For $N = 19$ an opposite effect is seen as the maximum of answers is obtained for an upward departure of two semitones. However, the distribution of responses is bimodal with the second maximum corresponding to the nominal pitch chroma.

Table 1. Combined results of Experiments I and Ia. Distribution of chroma identifications presented as pitch departure in semitones from the nominal pitch chroma. Pitch deviation of 0 semitones indicates correct response.

Pitch shift (semitones)	Lowest harmonic number (N)								
	7	10	11	12	13	14	15	16	19
-6			1		3		1	3	15
-5		1	1	2	11	1	3	7	34
-4		4		1	48	8	11	17	41
-3	14	11	3	4	58	65	47	44	60
-2	47	53	43	52	85	156	211	101	94
-1	31	41	47	97	111	289	320	259	149
0	854	844	829	757	484	359	283	352	172
1	32	25	57	67	120	70	59	106	104
2	3	18	17	16	56	40	27	49	215
3	18		2	3	14	11	24	20	93
4	1	3			8		13	24	14
5				1	2	1	1	18	9

Results of Experiment II are shown in Fig. 5 (group means) and Fig. 6 (individual results), as a function of the number of harmonics of a complex tone, separately for tones with lowest harmonic number of $N = 10$ and $N = 16$. Figure 5 also includes the results obtained by HOUTSMA and SMURZYNSKI (1990) for melodic intervals.

For tones with lowest harmonic number $N = 10$ the group means closely agree with HOUTSMA and SMURZYNSKI'S (1990) data (Fig. 5), especially when the tones comprise three or more harmonics ($M \geq 3$). Percentage of correct pitch identifications is highest for $M = 5$ and only slightly decreases for $M = 7$ and 11. Pitch recognition notably decreases for tones comprising two or three harmonics. For $N = 16$ the data compared agree only for $M = 2$ and diverge for tones with larger number of harmonics (Fig. 5).

The data of HOUTSMA and SMURZYNSKI (1990) show that increasing the number of harmonics improves identification of musical intervals whereas the present data demonstrate an opposite effect, as identification gradually worsens, starting from $M = 5$. Individual results (Fig. 6) generally follow the tendency apparent for group means in Fig. 5, although dispersion of responses is larger for $M = 16$ than for $N = 10$. It also should be noted that Experiments I and II included two common conditions: [$M = 11, N = 10$] and [$M = 11, N = 16$]. The group means obtained in those conditions, plotted in Fig. 2 for Experiment I and Fig. 5 for Experiment II, differ by less than 4%.

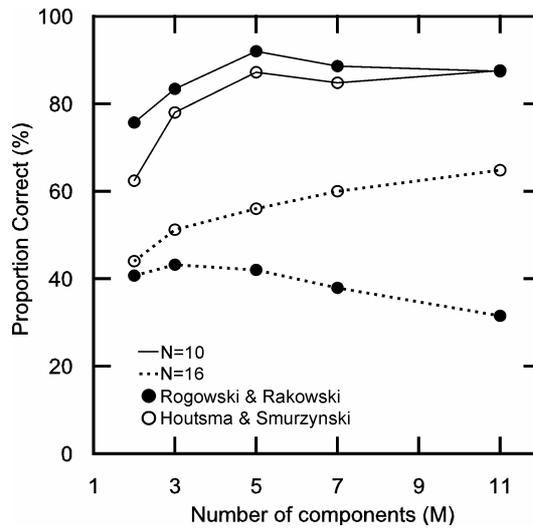


Fig. 5. Percentage of correct chroma recognitions in Experiment II as a function of the total number of harmonics of a residual tone. Closed circles indicate group means obtained for six listeners. Shown also are data reported by HOUTSMA and SMURZYNSKI (1990) for musical intervals (open circles). Results for tones with lowest harmonic $N = 10$ are connected by solid line and those for $N = 16$ by dotted line.

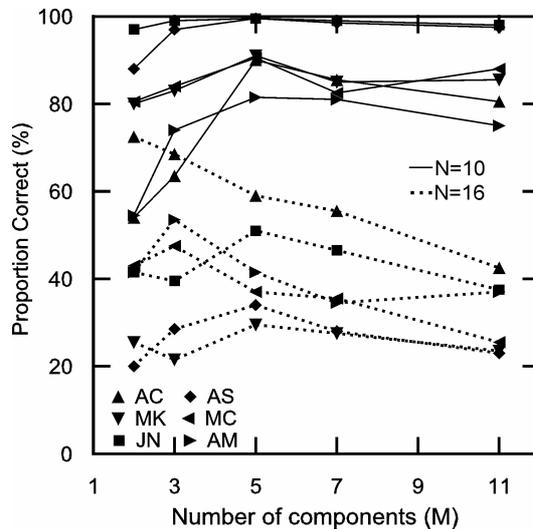


Fig. 6. Percentage of correct chroma recognitions in Experiment II. Individual data are shown for two values of N .

As shown earlier in Fig. 4, results of listener JN were inconsistent with those of other listeners in Experiment I. For JN percentage of correct identifications decreased to 47.5% for $N = 16$ and raising the lowest harmonic to 19 did not worsen identification significantly. This finding was similar to the pattern of data

obtained by HOUTSMA and SMURZYNSKI (1990). To examine the possible cause of such an inconsistency of listener's JN data with the rest of listeners, Experiment I was exactly repeated after one year for JN and also for listener AS, whose data were most divergent from JN for $N = 19$. Figure 7 shows the data obtained in the original experiment (closed symbols, data replotted from Fig. 4) and in the replication (open symbols). As seen in Fig. 7, the results of listener JN are nearly identical in both experiments. In the case of listener AS the data compared are generally in agreement, although for $N = 13$ the percentage of correct identifications is somewhat higher in the replica. Such a small difference is probably a random effect resulting from a small number of collected responses (ARANOWSKA and ROGOWSKI, 2000).

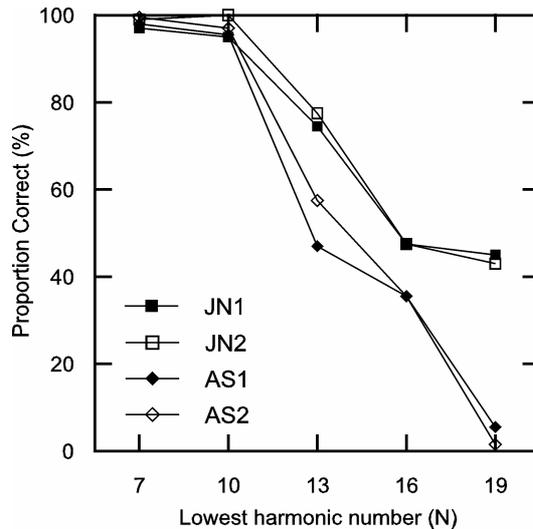


Fig. 7. Percentage of correct chroma recognitions. Individual results of listeners JN and AS obtained in Experiment I (closed symbols) and in a replicated experiment (open symbols).

4. Discussion

The main purpose of this study was to examine whether a method consisting in absolute identification of pitch chroma, i.e., the musical name of a tone, may be used as a reliable tool for the assessment of pitch strength. The present data were compared with the results of an experiment reported by HOUTSMA and SMURZYNSKI (1990) in which musically competent listeners were required to identify melodic intervals produced by two residue pitches. A comparison of results, obtained for tones that were nearly identical in both experiments, may provide some new insight into the phenomena underlying the perception of residue pitch and the effect of pitch strength.

It is readily apparent in Figs. 2 and 5 that the results of the experiments reported here generally agree with those of HOUTSMA and SMURZYNSKI (1990) for tones of high pitch strength. However, for tones of low pitch strength identification of melodic intervals is much better than identification of the chromas of single tones. The divergence between identification of musical intervals and direct identification of pitch chromas may be caused by various effects, some of which are discussed below.

(1) Figure 4 shows that in the case of all but one listeners identification of the pitch chroma of a tone with lowest harmonic $N = 16$ is better than identification of the chromas of tones with $N = 15$ and $N = 19$, represented by adjacent data points on the graph. Unlike for other tones used in the experiment, the pitch chroma corresponding to the missing fundamental of a tone with lowest harmonic $N = 16$ is strongly reinforced by this harmonic. The 16th harmonic has the same pitch chroma as the missing fundamental, only is by four octaves higher. In an array of harmonics with equal amplitudes the lowest one and the highest one are usually heard most clearly. This is caused by a more general phenomenon which may be called "the spectral-edge effect" (RAKOWSKI, 1968; FASTL, 1971). In the case described above the lower edge, rather than higher edge, of the spectrum may be heard most clearly as it is located in a sensitive part of the ear's frequency characteristic.

When the listener's task is to identify a melodic interval formed by two residue pitches there are cases in which an interval may be correctly identified by listening not to the residue pitch but to the pitch of a physically existent single harmonic, which changes in pitch by the same interval as the missing fundamental. Such a listening strategy may be used when the lowest harmonic number is the same in both tones that form an interval. HOUTSMA and SMURZYNSKI (1990) were aware of such a possible artifact therefore they randomized the lowest harmonic number within a range of ± 1 around the nominal N value. However, even though randomization was applied, the lowest harmonic number remained the same in one-third of the intervals which made it possible to identify the interval by listening to the spectral-edge pitch jumps.

As noted above, the strength of residue pitch increases when the residue pitch and the edge tone have the same chroma. In the experiments of HOUTSMA and SMURZYNSKI (1990) two melodic intervals might have been created simultaneously in various regions of the pitch scale: one formed by residue pitches corresponding to the missing fundamentals and the other one produced by the lowest existing harmonics in the tone spectra. When the strength of residue pitch was high the listeners were able to identify correctly the residue pitch interval and neglected the spectral-edge effects. When the lowest harmonic number was raised and the sensation of residue pitch became weaker, the listeners might have focused their attention on the interval produced by the most strongly exposed, lowest existing harmonic. Moreover, the two coexisting percepts of intervals might interact so that the interval formed by residual pitches might possibly be reinforced or

weakened by that produced by the spectral edges. When the intervals formed by spectral edges and by residue pitches are similar in size the identification level may increase. It should be noted that randomization of the lowest harmonic number (N), used by HOUTSMA and SMURZYNSKI (1990) to reduce the spectral-edge effect, became less effective when N was raised. For $N = 19$, in more than 3/4 cases, including 1/3 of intervals formed by tones with the same N number, an interval produced by the spectral-edge pitches differs from intervals formed by residue pitches by less than a semitone (while for $N = 7$ this difference exceeds two semitones in 2/3 of the intervals). When the lowest physically present harmonic is high ($N = 18, 19$ or 20) it is difficult or even impossible to hear an interval produced by two residue pitches and listeners may turn their attention to the spectral-edge pitch jump which practically remains very near or even within the same broad musical interval category (RAKOWSKI, 1976; RAKOWSKI, 1978; RAKOWSKI, MISKIEWICZ, 1985) as the interval produced by residue pitches.

One may ask a question, whether the spectral-edge effect is really an effective cue for identification of musical intervals in very high frequency regions? Although BURNS and FETH (1983) found that melodic intervals produced by pure tones may be correctly identified even at frequencies above 10 kHz, other researchers were more skeptic and argued that musical intervals and melodic sequences cannot be recognized above 4÷5 kHz (WARD, 1954; ATTNEAVE, OLSON, 1971; OHGUSHI, HATOH, 1991). It should be noted that when the lowest harmonic is raised to $N = 19$ nearly all spectral components of the stimuli used in experiments described here are located in a frequency range between 3.7 and 8.5 kHz.

(2) Musical intervals are part of a categorized within-octave pitch-distance system comprising a strict number of units. However, when exact recognition of a unit is difficult or seems impossible to the listener, an additional helpful cue may be obtained by using uncategorized, natural pitch-distance classes or categories (RAKOWSKI, 2009). Comparing two natural classes of pitch distance, such as *very small pitch distance* and *small pitch distance*, would help the listener first to decide that an investigated interval belongs to a given class, for instance *very small pitch distance* comprising seconds and thirds, and then guess by choosing one out of three or four very small intervals rather than one out of seven. In such a way of guessing the probability of choosing the right answer markedly increases.

(3) There is an important difference between the procedures of identification used in the two kinds of experiments discussed here. In the present study all 12 categories of pitch chroma were potentially accepted, therefore the level of random guessing was 1/12 (8.3%). In HOUTSMA and SMURZYNSKI'S study (1990) the listeners knew that the set of stimuli comprised only seven intervals, from minor second to perfect fifth, therefore the level of random guessing was 1/7 (14.3%).

(4) Identification of musical intervals might have been improved in HOUTSMA and SMURZYNSKI'S (1990) experiment as the listeners received correct-answer feedback. In the present experiment no feedback was given. Anecdotal observa-

tions show that correct-answer feedback does not improve absolute identification of pitch but this may not be the case in identification of musical intervals.

(5) The results obtained by HOUTSMA and SMURZYNSKI (1990) were smoothed due to randomization procedure. The transition from a range of good chroma identification to poor identification is more abrupt in present data.

All the effects described above may be partly responsible for the differences between the results of the two musical tasks compared here: identification of the chroma of the residue pitch of a single tone and identification of melodic intervals produced by two tones. A definite answer to the question which of the two functions presented in Fig. 2 illustrates more truly the real properties of the auditory system may provide an important insight to the theory of hearing. Giving full credit to the method of interval recognition supports the theories which assume that spectral components of a complex tone not necessarily have to be resolvable by the auditory system to produce a sensation of distinct residue pitch. If future experiments attest to the validity of pitch strength assessment through identification of pitch chroma by musicians with absolute pitch, the theories of "resolvable components" may restore their dominant position in the literature.

Before formulating conclusions of this study special attention should be given to individual results of the listeners. As mentioned before, the listeners were selected from a large population of music students as having most accurate and stable absolute pitch. A typical effect observed for this group is a common general trend of results despite a relatively large variability of data across listeners. Such an effect is apparent in Fig. 3 and Fig. 4: the data of all but one listeners show that identification of pitch chroma decreases as the lowest, physically existent harmonic of a tone is moved higher. An inconsistency with this tendency is seen in the data of listener JN, for tones with lowest harmonics $N = 16$ and $N = 19$. The relatively high identification score for $N = 16$ may be easily explained by the previously discussed spectral-edge effect which reinforces the residue pitch of the missing fundamental. On the other hand, the 44% chroma recognition obtained by JN for tones with $N = 19$ is inconsistent with the results of the four other listeners whose identification scores were either 14% or at a level of random guessing. The results of JN are in better agreement with HOUTSMA and SMURZYNSKI'S (1990) data who reported that identification of musical intervals produced by tones with lowest harmonic number $N = 19$ was about 56%. The reason for such an inconsistency of listener's JN data with rest of the group remains unknown and probably might be attributed to peculiar, individual characteristics of sound perception. As shown above, the unexpected results of listener JN were obtained once more with surprising accuracy after a period of one year. RITSMA (1967) found substantial, inter-subject differences in pitch perception of high-frequency components of complex tones. Perhaps an explanation for JN's peculiar performance will be found in further experiments conducted with the participation of that listener.

One more comment is needed as to the results of Experiment II, in which the number of harmonics, M , was the experimental variable and lowest harmonic number, N , the parameter. Results of Experiment II and those of the corresponding experiment reported by HOUTSMA and SMURZYNSKI (1990) are in close agreement for $N = 10$ and demonstrate opposite tendencies for $N = 16$. In the present study identification of pitch chromas gradually worsens with increasing number of high harmonics ($M > 3$). This finding suggests that increasing the number of high harmonics results in a weaker sensation of residue pitch. Due to informational masking (POLLACK, 1975) the high spectral components may to some degree mask the residue pitch of the missing fundamental. As seen in Fig. 5, no such a masking effect was found by HOUTSMA and SMURZYNSKI (1990). Moreover, the percentage of correct identification obtained in their study for tones with $N = 16$ increases with M . In that special case, like in other cases, the melodic interval identification method appears more effective than identification of pitch chroma in retrieving the pitch of the missing fundamental of a harmonic complex tone. Nevertheless it seems that choosing $N = 16$ as representing the “high-numbered- N ” residual sounds was not the best choice due to its strong “spectral-edge” effects.

5. Conclusions

In the present study a new method was proposed for direct assessment of the pitch strength. Pitch strength is derived from the percentage of correct pitch chroma recognitions obtained from musicians with absolute pitch. The relative simplicity of the procedure of pitch assessment and high repeatability of judgments all speak to the utility of the new method. Considering that the assessment of pitch strength with the use of musical interval identification may be affected by a variety of judgmental effects, the new method proposed here seems to be more reliable and accurate. The resolution of new method in N domain is better than the resolution of musical interval identification method.

A practical problem related with the use of the new method is the difficulty in finding listeners with faultless and stable absolute pitch. There is yet another problem which in many cases may limit the application of this method. A set of sounds, whose pitch strength is to be assessed, should be directly addressed to the equally-tempered tuning system based on a standard frequency, the same as memory standards of all the absolute-pitch listeners. In the present study this was achieved through changing fundamental frequencies of investigated sounds by 35 cents downward.

Results of the present study are in good agreement with the general rules of “receiving the missing fundamental” (MOORE, 1997). According to these rules, active harmonic components do not exceed the 20th harmonic or a frequency of 5000 Hz.

The results obtained with the new method were compared with those reported by HOUTSMA and SMURZYNSKI (1990) who investigated the pitch strength of practically the same sounds using the method of musical interval identification. Results obtained by both methods compared were convergent for tones with high pitch strength, such that both the musical name (chroma) of a single tone and the musical interval formed by two tones could be readily identified. These were cases when the sound spectrum contained mostly harmonics of not very high order, easily resolvable by the ear. However, when the tones comprised only unresolvable harmonics of very high order the new method yielded a very low pitch recognition level of about 20%, while identification of musical intervals, as reported by HOUTSMA and SMURZYNSKI (1990), remained stable at a much higher level of about 60%. While discussing the obtained results the authors perform short analysis of the possible artifacts that might have influenced assessments of the investigated sounds' pitch strength in the method of musical intervals identification. Most of them concern supplying additional cues in proper recognition of musical intervals in those cases when spectra of sounds constituting the intervals contain only harmonics not resolvable by the ear.

The present investigations as well as those reported by HOUTSMA and SMURZYNSKI (1990) should be considered as case studies due to the fact that the data were collected from a small number of listeners (depending on the experiment, five and two listeners in HOUTSMA and SMURZYNSKI'S study and five and six in the present one). The differences between group results of the studies might be therefore partly caused by individual characteristics of sound perception in subjects.

Further investigations are needed to obtain an explanation of the discrepancies between the results obtained with the use of the method proposed here and the method consisting in identification of musical intervals.

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