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Pitch identification of simultaneous diotic and dichotic two-tone complexes

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This study examines subjects' ability to recognize the pitches of two missing fundamentals in two simultaneous two-tone complexes whose partials are distributed in various ways between subjects' ears. The data show that identification performance is affected on different levels. Limited frequency resolution in the peripheral auditory system can degrade performance, but only if none of the four stimulus partials is aurally resolved. Identification performance is only weakly dependent on the manner of distributing partials between the ears. In some cases it was found that, probably at a very central level (e.g., attention), the identification processes of both simultaneous pitches interfere with one another. Some subjects are more likely to identify the pitch of one two-tone complex when the harmonic order of the other complex is higher than when this harmonic order is lower. Finally, some subjects tend to hear the complex tones analytically, i.e., perceive pitches of single partials instead of the missing fundamentals for some distribution of partials between the ears.

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INTRODUCTION

In an earlier study (Beerends and Houtsma, 1986), we examined subjects' ability to recognize two missing fundamentals in two simultaneous two-tone complexes with one complex tone in each ear. Each complex, consisting of two adjacent partials, was presented to a different ear so that the distribution of partials over the ears coincided with the correct grouping of the partials.

In the present article, similar identification experiments are reported that use three other distributions of partials over the ears. In one configuration, the two complex tones are presented diotically, with all four partials going to both ears. In two other configurations, called dichotic (1) and dichotic (2), stimuli are presented in such a way that each ear receives only one partial of each two-tone complex. For purposes of comparison, we will also reintroduce some of the results of our earlier study and refer to that condition as dichotic (0). The four stimulus presentation conditions all together are illustrated in Fig. 1.

In contrast to the dichotic (0) condition, the diotic presentation and, to a lesser extent, the dichotic (1) and dichotic (2) presentations, can cause two frequencies of different tone complexes to nearly coincide and end up in the same ear. When they differ by less than 10%, they are likely to produce roughness or beats and could be unsuitable as conveyors of virtual pitch. With the data obtained in this study, we can investigate the correctness of the assumption that only partials resolved in the auditory periphery contribute to the sensation of complex tone pitch (Terhardt, 1970; Houtsma and Goldstein, 1972; Plomp, 1976).

Comparison of identification results obtained under the four presentation conditions is likely to tell us more about the internal grouping and interpretation of the perceived partials. According to the optimum processor theory for the pitch of a missing fundamental (Goldstein 1973), the per-

ceived pitch is a maximum likelihood estimate of the fundamental of a harmonic template that gives the best fit to the observed (noisy) stimulus frequencies. In the case of two fundamentals to be estimated from two groups of two partials, it can be shown that, in terms of that theory, correct estimation depends, to a large extent, on the prior knowledge the processor has about the proper grouping and interpretation of those perceived partials. Because in this study the distribution of partials over the ears was varied systematically, the identification results are likely to show under what conditions there is such advanced knowledge.

Finally, one can view identification of the missing fundamentals of two simultaneous complex tones as two separate pitch identification processes. In terms of the optimum processor theory, it is easy to show that, as long as the four noisy observations of the four stimulus frequencies are represented by independent Gaussian random variables, the maximum likelihood estimates reduce to two separate estimates of the respective (missing) fundamentals. In reality, however, we may be dealing with processes that interfere with one another at a very central level. For instance, perception of simultaneous pitches could be a serial process in which the clearer, more salient pitch of the two is identified first, whereas the weaker one is not only harder to identify because it is weak, but also because it may get less attention and is more corrupted by memory noise. This effect, which we will call *central interference*, is investigated by considering the scores for each individual complex tone as a function of both its own physical parameters and of the parameters of the other (simultaneously present) complex tone. Specifically, we will see whether the score for a two-tone complex is higher when the other tone has a higher harmonic order (less salient) than when the other tone is of lower harmonic order (more salient).

The experiments and the raw results are described in Sec. I. In Sec. II, the data are analyzed in different ways such

FIG. 1. Four different partial distributions with two simultaneous two-tone complexes. Dichotic (0) data taken from Beerends and Houtsma (1986). Other paradigms used in this study.

that the effects of limited cochlear resolution, grouping information, and central interference can be quantified. Section III presents a general discussion and a summary in the form of conclusions.

I. EXPERIMENTS

A. Procedures

Subjects were asked to identify the pitches of two different simultaneously sounding notes, each represented by two successive random harmonics. One note comprised the frequencies $f_1 = mf_{01}$, $f_2 = (m+1)f_{01}$, the other the frequencies $f_3 = nf_{02}$, $f_4 = (n+1)f_{02}$. Note duration was 600 ms. The fundamentals f_{01} and f_{02} were both different elements of the set of frequencies 200, 225, 250, 267, 300 Hz (notes "do, re, mi, fa, so"), of which f_{01} always designated the lower fundamental. Three different kinds of presentations were used (Fig. 1): diotic— f_1, f_2, f_3, f_4 to both ears; dichotic (1)— f_1, f_3 to one ear and f_2, f_4 to the other ear; dichotic (2)— f_1, f_4 to one ear and f_2, f_3 to the other ear. Both (lower) harmonic numbers m and n varied independently between values of 2 and 10. On every trial, subjects were asked to identify f_{01} and f_{02} by pressing two out of five possible buttons on a response box. All subjects possessed the necessary musical skills as all scored better than 99% if pure tones were used instead of two-tone complexes.

Each of the 810 different stimuli that were possible was presented about six times on average, for a total of 4500 trials per subject. All stimuli were presented 20 dB above masked threshold, with 30-dB SL white noise, bandlimited between 50–5000 Hz, as a masking background. This noise masked unwanted and potentially disturbing aural distortion prod-

TABLE II. Percent correct scores for one note correct identification given that the other note is represented by harmonics l and $(l+1)$, $Pc(k;l)$, in a diotic two-note identification task, averaged over four subjects. Chance level is 40%.

	$l=2$	3	4	5	6	7	8	9	10
$k=2$	92	90	92	96	96	97	91	94	94
3	91	93	87	89	95	93	93	96	97
4	78	79	83	85	90	92	94	97	95
5	65	69	61	82	86	82	89	90	93
6	67	68	69	78	78	81	84	90	93
7	69	70	74	71	72	81	82	88	88
8	56	54	50	51	51	60	67	71	67
9	43	44	43	44	39	43	45	55	55
10	42	46	42	47	51	53	59	53	52

ucts (Plomp, 1965; Goldstein, 1967; Humes, 1980). Further details of the experimental procedure can be found in our earlier article (Beerends and Houtsma, 1986).

B. Results

The raw data of the experiments consisted of the trial records containing the presented fundamentals f_{01} and f_{02} , their lower harmonic numbers m and n , and the subjects' two responses R_a and R_b . A simple way of presenting the data is to pool the responses to the various fundamental frequencies and harmonic numbers and to simply count the trials for which both notes were correctly identified. These percentages of "two notes correctly identified" are shown in four columns of Table I for four subjects and four different stimulus presentations. [The data of the dichotic (0) condition are taken from Beerends and Houtsma (1986).]

Another way of representing the data is to consider the identification of each note individually as a function of both its harmonic representation and the harmonic representation of the other note (regardless of the response to that other note). This score, designated as $Pc(k;l)$, then represents the correct identifications of f_{01} for $k=m$ and $l=n$, as well as the correct identifications of f_{02} for $k=n$ and $l=m$.¹ These scores, averaged over all four subjects, are shown in Table II for the diotic presentation. The average scores of the dichotic (1) and dichotic (2) conditions, also for all subjects, are given in Table III.

If the identification of each individual note were independent of the representation of the other (simultaneous) note, the scores along each row of the matrices in Tables II and III should be constant. This, however, is clearly not the

TABLE I. Identification scores for "two notes correct" and "one note correct." The scores for two notes correctly identified are averaged over all k, l and have a chance level of 10%. The scores for one note correct identification, $Pc(k;l)$, are averaged for $k < l$ and $k > l$ and have a chance level of 40%. The 95% confidence intervals are in the order of 1.5%.

Subject	Dichotic (0)			Diotic			Dichotic (1)			Dichotic (2)		
	two correct	one correct $k < l$	one correct $k > l$	two correct	one correct $k < l$	one correct $k > l$	two correct	one correct $k < l$	one correct $k > l$	two correct	one correct $k < l$	one correct $k > l$
MZ	64	90	71	65	90	73	55	80	69	59	85	70
AH	58	91	64	49	90	55	45	89	51	44	87	52
BP	54	87	63	51	88	59	50	89	56	49	89	55
JH	40	89	48	38	87	46	32	82	43	32	82	43

TABLE III. Percent correct scores for one note correct identification given that the other note is represented by harmonics l and $(l + 1)$, $Pc(k;l)$, in a two-note identification task, averaged over the presentations dichotic (1) and (2) and four subjects. Chance level is 40%,

	$l = 2$	3	4	5	6	7	8	9	10
$k = 2$	94	89	87	96	96	96	88	94	95
3	89	89	87	92	93	92	90	94	95
4	80	82	82	87	92	94	90	95	97
5	64	60	62	70	77	76	77	80	84
6	59	63	61	72	72	72	72	79	84
7	66	67	65	67	73	78	82	83	85
8	58	55	50	50	49	57	61	68	72
9	35	40	36	40	45	41	47	51	47
10	38	42	36	42	45	43	49	51	49

case. If we take, for instance, the row $k = 6$ in Table II, we see that, for $k < l$, the average $Pc(k;l)$ is about 87%, whereas, for $k > l$, the average one note correct score is about 71%. Only a very small part of this difference can be attributed to chance-level statistics that are inherent to our choice of experimental paradigm. The results, therefore, suggest that the pitch of one complex tone is recognized more easily when the other simultaneous complex tone is represented by higher-order harmonics than when this other tone is represented by lower-order harmonics. The upper-half and lower-half score matrices $Pc(k;l)$ were, therefore, averaged separately for each of the four presentation conditions and are shown in Table I under the headings "one correct" for $k < l$ and $k > l$.

II. INTERPRETATION OF RESULTS

A. Cochlear interference of partials

One of the assumptions of the optimum processor theory is that virtual pitch can be conveyed by those partials that are resolved in the cochlea. This assumption was primarily based on observations that the pitch of a missing fundamental is effectively heard only when the harmonics of a complex tone are below the order of about 10 (Terhardt, 1970; Houtsma and Goldstein, 1972; Plomp, 1976). This assumption can be tested from a different angle with the data of the present experiment because, with diotic presentation of two simultaneous complex tones, there can be partials in one ear with very small frequency differences, even if all partials are of relatively low harmonic order.

To assess the effect of interference between partials on recognition of the respective pitches, the stimuli were rank ordered according to an arbitrary distance $d = \sqrt{d_1^2 + d_2^2}$, where d_1 is the smallest frequency difference between two stimulus partials and d_2 the next smallest difference, expressed as percentages. In order to focus on the effect of unresolved partials of low harmonic order, the analysis was restricted to complexes with harmonics of order 5 or less. This assures that scores will generally be high for presentation conditions where all partials are cochlearly resolved, so that the effect of unresolved partials in other conditions will become maximally visible.

When scores of correct identification of both simultaneous pitches, averaged over all four subjects, are measured in terms of d , one finds rather constant scores of about 70% correct for the dichotic (0) condition, even for small values

of d . This is not surprising since, for that condition, partials whose frequencies are close together went to different ears. For the diotic condition, the results are almost the same, except that a drop to about 50% correct is observed when d is smaller than 5%. This measured drop is based, however, on a total of about 45 experimental trials, because the situation where d fell below 5% did only occur twice in the stimulus set. If identification scores are expressed in terms of d_1 , the smallest frequency difference between any two partials, no significant score difference between the two presentation conditions is found.

A similar picture is obtained when performances for the dichotic (1) and dichotic (2) conditions are compared. Performance drops noticeably only if frequency differences between the partials going in each ear are both small, i.e., if none of the four partials that make up the stimulus is cochlearly resolved.

The most important implication of this finding is that apparently nonresolved partials can help convey the sensation of virtual pitch under certain circumstances. For instance, if a complex tone comprised of the frequencies 1067 and 1333 Hz is sounded together with another complex containing the frequencies 800 and 1000 Hz, the pitches 200 and 267 Hz are heard, even with all partials presented to both ears. Apparently the frequencies of the unresolved partials of 1000 and 1067 Hz are still transmitted to the brain as a single frequency equivalent, which, together with the other resolved frequencies, can convey the percept of two simultaneous virtual pitches.

B. Internal grouping of partials

A comparison between the appropriate columns of Table I, and of the data of Table II with those of Table III, leads one to conclude that note identification performance is not very sensitive to the manner in which the partials are distributed between the ears. Even if the recognition data were exactly identical under the four presentation conditions considered, we still could not tell right away whether the brain processes the four observed (partial) frequencies without any prior grouping knowledge in all four cases [i.e., ignores the "correct" information in the dichotic (0) condition and the "incorrect" information of the dichotic (1) and dichotic (2) conditions], or just happens to have this knowledge always available by some other means. This question can be answered, however, by comparing our experimental data with two sets of model-simulated results, one generated with and the other without supplied information of the correct grouping.

The simulation experiments were based on a generalized formulation of Goldstein's (1973) optimum processor theory and a decision model of the subjects' response strategy, both given in Beerends and Houtsma (1986). The generalized formulation of the optimum processor theory was implemented through Monte Carlo simulation algorithms that transform the physical frequencies $f_1, \dots, f_4$ into four independent random variables $x_1, \dots, x_4$. With these random variables and the decision model, the two perceived pitches were calculated both with and without inserting information about the correct grouping of the partials into the model.

For the first algorithm, the average sigma function shown in Fig. 5 of Beerends and Houtsma (1986) was used for the transformation of the frequencies into the random variables. No information about the correct grouping of partials was supplied. This algorithm produced a list of stimuli for which occasionally incorrect internal grouping occurred, leading to pitch(es) within the answering range but differing from the two presented missing fundamentals. This subset of stimuli contained about 30% of all the stimuli we used and will be referred to as G. The complementary subset, which only contains stimuli for which grouping errors never occurred, will be referred to as NG.

Next, we computed from the subset NG a sigma function for each subject in each experimental condition (using a method described in Beerends and Houtsma, 1986). With each of these sigma functions, two sets of data were produced by separate Monte Carlo simulation algorithms, one with and one without explicitly supplied information about the correct grouping of partials. The results are shown in Fig. 2.

The scores of both algorithms in the subsets NG are about the same as the empirically obtained scores, yielding the consistency one expects. The discrepancies that do occur form a measure of the precision of this simulation method. The predicted scores in the subsets G show that the behavior of the subjects in dichotic (0) presentation is in excellent agreement with the assumption that they had prior knowledge about the proper grouping. For the other stimulus presentations we see that, for most subjects, the experimentally obtained scores are in much closer agreement with the assumption that prior knowledge of grouping is present than with the assumption that such knowledge is absent. The only

weak exception to this rule can be found in the experimental data of JH for the condition dichotic (1), which ends up about halfway between the two simulated scores.

C. Central interference and analytic listening

Cochlear interference of partials discussed in part A of this section and incorrect internal grouping of partials discussed in part B occur only when frequencies of two or more partials are close. We will now discuss another, even more central, source of possible identification confusion that can play a confounding role also when signal partials are widely separated. This source was already mentioned in Sec. I, where data showed, in general, that the pitch of either complex tone is recognized more easily when its harmonic order is lower than that of the other complex tone.

In order to quantify the degree of central interference between the two pitch identification processes, performance is expressed in terms of a function that represents the optimum processor's probability of correctly estimating the harmonic order of either complex tone (Goldstein, 1973; Beerends and Houtsma, 1986). Such functions are independent of details of the experimental paradigm, and, therefore, have more general validity than the actually measured score functions. Two sets of such probability functions were derived from the scores $P_c(k;l)$ given in Sec. I B. The first set, called $Pr_\alpha [\hat{k} = k]$, represents the probabilities that the processor's harmonic-order estimate $\hat{k}$ equals the actual harmonic order k of that complex tone, under the condition that the harmonic order of the other (simultaneous) complex tone is higher ($k < l$). The second set, $Pr_\beta [\hat{k} = k]$, represents these same probabilities when the harmonic order of the other complex tone is lower ($k > l$). Diagonal entries were not used in the calculation of $Pr_\alpha [\hat{k} = k]$ and $Pr_\beta [\hat{k} = k]$. The mathematical details of the computation of the functions Pr_α and Pr_β from the scores $P_c(k;l)$ are given in the Appendix. If there were no central interference between the two processes, the functions Pr_α and Pr_β would be identical.

The results, computed individually for each subject and each presentation condition, are shown in Fig. 3. This data representation shows three interesting features. The first is that the degree of central interference, as measured by the similarity of the two functions, is very subject dependent. For MZ, the functions almost coincide, implying that central interference is minimal for all four conditions. Subjects AH and BP exhibit quite similar Pr_α and Pr_β functions under the condition dichotic (0), i.e., when the correct grouping information for partials is externally provided, but shows a distinct divergence of these functions (implying increased central interference) when grouping information is not provided or presented in a misleading way. Subject JH shows a large difference between Pr_α and Pr_β under all four stimulus presentation conditions.

The second feature worth mentioning is that, looking down each column of Fig. 3, one observes that, for subjects AH and BP, the Pr_α function (triangles) remains rather much the same, whereas the Pr_β function (squares) decreases. This effect can also be seen in Table I by comparing the "one correct" scores in the four conditions. From these observations, we can conclude that, for two subjects, the in-

FIG. 2. Simulated and experimental identification scores for "two notes correct" for four subjects and four stimulus conditions. Scores are given for the subsets G, which is sensitive to grouping errors and for NG, where grouping errors do not occur. Solid lines give the experimental results, dashed lines are predictions of a simulation algorithm with supplied grouping information. Dotted lines are predictions made without this information. Missing lines indicate perfect agreement between prediction and measurement. All predictions are made with Goldstein's pitch theory and a sigma function derived from the subset NG.

FIG. 3. Two sets of probabilities that a maximum likelihood estimator correctly estimates the harmonic number of one complex tone, for four subjects and four stimulus conditions. The first set, $\Pr_\alpha [\hat{k} = k]$ (Δ), gives the probabilities of a correct harmonic number estimate (and, consequently, a correct identification of the note) when $k < l$. The second set, $\Pr_\beta [\hat{k} = k]$ ($\square$), gives the same probabilities but for $k > l$.

creased complexity of the recognition task only affects the pitch represented by the higher harmonic numbers, i.e., the less salient pitch.

The third feature to be discussed is the occasional non-monotonicity of the $\Pr_\alpha$ and $\Pr_\beta$ functions. Scores generally decline with increasing k , but occasionally show a dip when k equals five or six and/or a local peak when k equals seven or eight. This seems to happen particularly under the dichotic (1) and dichotic (2) conditions for subjects MZ and JH. The most plausible explanation is that these subjects have a tendency to perceive a complex tone analytically, i.e., associate its pitch with the frequency of one of its partials or an octave transposition thereof (when a complex tone contains harmonics 2, 4, or 8). This happens particularly when partials in one ear have no common fundamental. That analytic pitch perception can play a confounding role in pitch experiments with complex tones has been shown at other occasions (Houtsma, 1979; Deutsch, 1972). Apparently, the increased complexity of the recognition task causes these subjects to listen more to the partial frequencies.

Finally, a detailed analysis of the central interference effects showed that they increase with spectral distance between the two simultaneous tone complexes.

III. DISCUSSION AND CONCLUSIONS

A. Discussion

When subjects, presented with two simultaneous complex tones, are asked to identify their respective pitches,

there are a number of issues that do not come up when the pitch of only one single complex tone is to be recognized. Three of these issues have been examined and quantified in this study.

The data analysis presented in Sec. II A indicates that interference of partials in the cochlea, due to limited frequency resolution, plays a really confounding role only if all four partials are (pairwise) unresolved. If only two partials are unresolved in either ear, the information still appears to be transmitted to the brain as a single frequency code reflecting the average frequency of the two unresolved tones. Together with the other two frequency codes, the two missing fundamentals (pitches) can be reconstructed. The fact that only pairwise interference between all partials of the two complex tones is a sufficient condition for pitch identification scores to drop significantly was also established with two simultaneous three-tone complexes when, under diotic presentation, three pairs of unresolved harmonics resulted (see Houtsma and Beerends, 1986, Fig. 6).

Subjects' ability to interpret and group simultaneous partials correctly (according to the actual structure of the complex tones) appears very robust against all our experimental attempts to confuse the subjects. Pitch identification scores were generally highest when the two-tone complexes themselves were dichotically separated, as occurred in the dichotic (0) condition, but were not much lower when complex tones were both split across the ears, as in the dichotic (1) and dichotic (2) conditions. A simulated control experiment with Goldstein's model, in which the grouping of partials was always imposed as it occurred at each ear in dichotic (1) and dichotic (2) presentation, invariably resulted in chance-level performance. This is rather strong evidence that our brain groups partials of simultaneous tone complexes on the basis of harmonic or tonal relationship, rather than ear input. A similar conclusion was reached by Deutsch (1975) and Butler (1979) from their experiments with dichotic melodic sequences.

One puzzling element remains, however. The very existence of a stimulus subset G, as described in Sec. II B, implies that the absence of explicit information of the correct grouping of stimulus partials often leads, for those stimuli, to the wrong internal grouping during the simulation. Such grouping is, nevertheless, based on harmonic relationships between partials, since the simulation algorithm (Goldstein's optimum processor model) simply attempts to find the best fitting harmonic templates. Our experimental data, however, show that for this stimulus subset G subjects perform as if they have advanced knowledge of the correct grouping of partials. The real source of this knowledge, therefore, remains unclear.

In Sec. II C, we showed that sometimes the correct identification of the pitch of a tone complex depends systematically on the harmonic order of the other simultaneous complex. The degree of this effect varied considerably between subjects. Its cause is, therefore, thought to be quite central and may very well have something to do with musical experience. Subject MZ, who exhibited the least of this *central interference* in her data, was also musically the most experienced.

The results of Sec. II A–C, together, imply that correct perception of the pitches of two simultaneous complex tones is easy when these tones are spectrally close (as long as not all partials are unresolvable), and becomes more difficult when complexes become spectrally separated. In musical practice, harmonic intervals as they occur in duets, or two part counterpoint, are usually scored for voices of instruments of similar timbre, i.e., having considerable spectral overlap. The use of instruments with very different timbres in such situations, for instance, one with predominantly low and another with mostly high harmonics, should, according to our findings, produce perceptual problems with the recognition of the notes.

Finally, the question could be raised whether, under the conditions of our experiments, subjects really identified simultaneous pitches rather than harmonic intervals. For instance, did they hear a “do” and a “mi” on a particular trial, or merely a major third? A first answer to this question is that mere interval recognition could never have led to the scores that were measured, because the ten possible answer combinations involved one minor second, three major seconds, two minor thirds, one major third, two perfect fourths, and a perfect fifth. If subjects could only identify harmonic intervals, their score could never have exceeded 60% correct, which was clearly not the case for low harmonic numbers (as can be seen in Table I in Beerends and Houtsma, 1986). Moreover, a ten by ten harmonic-interval confusion matrix shows that subjects hardly ever confuse intervals that are nominally the same, such as the major seconds do–re and fa–so, the minor thirds re–fa and mi–so, or the perfect fourth do–fa and re–so. Under all presentation conditions, we found, however, some dependence of identification scores on interval size, similar to earlier findings for the dichotic (0) condition (Beerends and Houtsma, 1986, Fig. 6).

B. Conclusions

The experiments show that, to a certain extent, subjects are able to use spectrally interfering components to calculate the missing fundamental. A noticeable decrease in correct identification only occurs if none of the stimulus partials is aurally resolved.

The distribution of partials over the ears has only a minor influence on the internal perceptual grouping. Subjects simply seem to pool partials from left and right ears before processing them centrally. In general, we suggest that, in normal everyday situations, where each note of a chord usually contains more than two partials, correct internal grouping of partials presents no problem for the perception of the various pitches.

The small differences in identification scores between the four conditions are primarily caused by central interference. Of the two pitches, of which one is usually more salient than the other, the more salient pitch inhibits, to some extent, correct identification of the less salient pitch.

Finally, in experiments where each ear received only one partial of each two-tone complex, some subjects show an increased tendency to hear the sound analytically, i.e., perceive pitches of individual partials.

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APPENDIX: THE UNDERLYING PROBABILITY FUNCTIONS

As shown in our previous article (Beerends and Houtsma, 1986, Appendix C), the percentage $P_c(k;l)$ of correct identification of the fundamental represented by the k th and $(k+1)$ th harmonics, regardless of the response to the fundamental that is represented by the l th and $(l+1)$ th harmonics, can be written as

$$P_c(k;l) = 20(4\Pr[\hat{k} = k] + 1) + 5(1 - \Pr[\hat{k} = k])(4 - 3\Pr[\hat{l} = l]). \quad (A1)$$

If we define two sets of underlying processor probabilities, $\Pr_\alpha[\hat{k} = k]$ for the identification in the case $k < l$ (identification of the more salient pitch), and $\Pr_\beta[\hat{k} = k]$ for identification in the case $k > l$ (the less salient one), we can write

$$P_c(k;l) = 20(4\Pr_\alpha[\hat{k} = k] + 1) + 5(1 - \Pr_\alpha[\hat{k} = k]) \times (4 - 3\Pr_\beta[\hat{l} = l]) \quad \text{if } k < l$$

and (A2)

$$P_c(k;l) = 20(4\Pr_\beta[\hat{k} = k] + 1) + 5(1 - \Pr_\beta[\hat{k} = k]) \times (4 - 3\Pr_\alpha[\hat{l} = l]) \quad \text{if } k > l.$$

If we take a certain stimulus with lower harmonic numbers m and n , with $m < n$, we can calculate a $\Pr_\alpha[\hat{m} = m]$ and a $\Pr_\beta[\hat{n} = n]$ from the matrix entries $P_c(m;n)$ and $P_c(n;m)$ by solving Eqs. (A2) for $\Pr_\alpha$ and $\Pr_\beta$. By averaging the $\Pr_\alpha$'s and $\Pr_\beta$'s that are calculated in this way, the scores as given in Fig. 3 are obtained.

For the points $\Pr_\alpha[\hat{k} = k = 10]$ and $\Pr_\beta[\hat{k} = k = 2]$, this method will not find a value because, for the set $\Pr_\alpha$ (derived from $k < l$), there are no stimuli ($k = 10; l > 10$), while, for the set $\Pr_\beta$ (derived from $k > l$), there are no stimuli ($k = 2; l < 2$). In one point, for subject JH in the dichotic (1) presentation with $k = 9$, a negative value for the probability was found. This indicates a failure in the decision model, and the probability in this point was set to 0.

For diagonal entries in the matrices $P_c(k;l)$, where both pitches are equally salient, we can estimate the underlying processor probabilities $\Pr[\hat{k} = k]$ by solving the quadratic equation (A1). In general, we may expect that $\Pr_\alpha[\hat{k} = k] \leq \Pr[\hat{k} = k] \leq \Pr_\beta[\hat{k} = k]$. This requirement was fulfilled for almost all datapoints.

¹The notation $P_c(k;l)$ designates the same quantity as $P_c(k|l)$ used in Beerends and Houtsma (1986). We preferred to change the notation since $P_c(k;l)$, as defined in text, is a function of two variables and not a conditional probability.

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