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PITCH OF SIMULTANEOUS COMPLEX SOUNDS WITH A SINGLE MISTUNED COMPONENT.

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1. ABSTRACT

When a single harmonic of a complex sound is mistuned, it influences the pitch of the complex unless it is mistuned by more than about 8% [1]. We have investigated how the mistuning of a single component influences the pitch of two simultaneous complex tones, with harmonic frequencies close to those of the single mistuned component. Specifically we have asked whether a harmonic that is exactly in tune with one harmonic series (eg 600 Hz to a 200 Hz fundamental) can still contribute to the pitch of another complex tone (eg 145 Hz fundamental) for which it is mistuned. Our experiments employed a pitch-matching task and used 410ms duration sounds. A 200 Hz series (first 12 harmonics) was paired with either a 145 or 155 Hz series, with both the third harmonic of the 200 Hz series and the fourth harmonic of the other series being replaced by a single tone of variable frequency. Subjects matched the two pitches in different sessions. Our results show that a single harmonic can contribute to the pitch of both simultaneous complex tones; it is not 'captured' by the series for which it is most in tune.

2. INTRODUCTION

Although the pitch of complex sounds which are close to a single harmonic series has been extensively studied [2] and quantitatively modelled [3, 4, 5], less attention has been paid to the more complex, but naturally common case of more than one harmonic series being present at a time. When two instruments (or voices) are sounding different pitches simultaneously, which partials contribute to which pitch?

One mechanism proposed for rejecting spurious harmonic peaks in calculating pitch in natural speech signals can be used to tackle this problem. The low-numbered, unresolved harmonics predominantly determine the musical pitch of a complex sound [6]. The 'harmonic sieve' [7] filters the components that have been resolved by the auditory system, passing only those that lie within some tolerance of a particular harmonic series. The basic sieve mechanism can be adapted to estimate multiple pitches [8]], with different sieve spacings independently estimating which harmonics are relevant to a particular fundamental. Alternatively, the sieve could be used to remove from further consideration those components that are close to one harmonic series. Such removal would be compatible with the Gestalt notion of Disjoint Allocation [9].

Relevant experimental evidence comes from two sources. First, the sieve's tolerance has been estimated by Moore et al. [1]. They measured the pitch shift associated with a single mistuned harmonic in a 12-tone complex. Overall their data showed that a partial that has a frequency within 3% of a harmonic value makes a full contribution to the pitch of a complex, but this contribution diminishes with further mistuning, falling to zero at about 8%. Second, Beerends and Houtsma have measured the accuracy with which musical listeners can judge the musical interval made by two simultaneous complex tones each consisting of two consecutive harmonics [10, 11]. The individual components could be played diotically, or dichotically, with the harmonics from the same fundamental either going to the same or to different ears. Their data was modelled by giving Goldstein's optimal processor theory [3] information about how the individual harmonics should be grouped into pairs. This grouping mechanism must operate predominantly according to harmonic relations rather than by which ear a component arrived at, since distributing the harmonics in-appropriately across the ears only had a very weak influence on the accuracy of musical interval judgements. Harmonicity was a more powerful grouping cue than ear.

Musical interval judgements to a subset of the data of Beerends and Houtsma [11], argue against the principle of Disjoint Allocation. They showed that a complex formed by two unresolved partials may contribute to the perception of both pitches. For instance, when the ear receives 800 and 1000 Hz plus 1067 and 1333 Hz, the 1000/1067 unresolved complex can contribute to both a 200 Hz and a 266 Hz pitch. The experiments reported here look in more detail at this issue using a paradigm that can directly measure the contribution that a particular component makes to a given pitch percept. We ask the following question: can a single partial contribute to the pitch of both of two simultaneous complex tones even if it is exactly harmonically related to one of the fundamentals?

We extend the paradigm used by Moore et al. [1] to the case of two simultaneous tones. Specifically, listeners hear two simultaneous complex tones which contain a mistuned component and attempt to match the pitch of each of the complexes in turn. The fundamentals are chosen so that the third harmonic of one fundamental is close in frequency (3%) to the fourth harmonic of the other fundamental. Then that component can be exactly in tune with one harmonic series, while potentially able to give the maximum pitch shift to the other series. We have used a fundamental of 200 Hz paired with one of either 145 Hz or 155 Hz. The 600 Hz harmonic of 200 is roughly 3% away from the 580 Hz harmonic of 145 and the 620 Hz one of 155. The two harmonics (580 & 600 or 620 & 600) are both removed and replaced by a single partial whose frequency is varied while we examine the pitch shift produced in either of the two complexes.

The first experiment establishes that pitch shifts similar to those reported by Moore et al, could be obtained with our particular stimuli. The second experiment measures pitch shifts to two simultaneous diotic tones with a single (potentially shared) partial mistuned.

3. GENERAL METHOD

As in Moore's original experiment [1], subjects were presented with a sequence of two complex tones in each trial. Their task was to adjust the pitch of the second tone so that it matched that of the first tone. The first (reference) tone could contain a partial that was shifted in frequency from its harmonic value. The second (adjustable) tone was strictly harmonic. Its fundamental could be adjusted by moving a roller-ball (mouse substitute) connected to the Apple Desktop Bus of a Macintosh II. The two sounds were produced 500ms after the subject pressed the roller-ball's button through the 16-bit DACs and anti-alisasing filters of a Digidesign Sound Accelerator board. Each reference tone was pre-computed on the Mac with a 10ms raised-cosine onset and offset, a steady state duration of 390ms and a sampling rate of 20.5kHz. The 410ms comparison tone was calculated during the 500ms time interval after the button press by concatenating the appropriate number of precomputed single periods with two-cycle onset and offset transients. Its period was changed by varying the playback rate around 30kHz. Each trial started with this period chosen at random from within the range; if a subject tried to adjust the sound outside the range, the period was reset at random within the range.

All partials had the same amplitude (corresponding to a level of 53dB SPL for a 1000Hz tone) and were added in sine phase. Stimuli were presented through a Sennheiser HD414 headphones in a double-walled sound-proof booth. Subjects could change the frequency of the comparison sound by moving a roller-ball up (increasing the pitch) or down (decreasing the pitch). This movement changed the position of a cursor, which was re-centered after each sound. A complete excursion of the cursor from the top to the bottom of the screen corresponded to an angular movement of the ball of about 2 radians and varied the fundamental by 3.2Hz. Subjects were encouraged to "bracket" the match several times before making the final adjustment. and had as long as they wished to perform the task. Each reference sound was matched 5 times in a quasi-random order in an experimental block that varied the degree of mistuning of a single partial. Each block took around one hour to complete (with rest breaks) and the order of experimental blocks was partly randomised across subjects.

4. EXPERIMENT 1

The first experiment establishes the validity of the experimental paradigm for our particular stimuli by measuring pitch matches to a 12-partial complex with a single mistuned partial.

4.1 Stimuli & Subjects

The three different reference tones consisted of the first 12 harmonics of 145Hz, 155Hz and 200Hz. For the 145Hz and the 155Hz tones the fourth harmonic was mistuned (from 580Hz and 620Hz respectively), while the third harmonic of the 200Hz tone was mistuned. The frequency of the mistuned component deviated from its harmonic value by ± 0, 5, 10, 15, 20, 30 and 40 Hz (roughly covering the percentage shifts used by Moore et al.). Three subjects were used. One (CJD) was experienced in psychoacoustical tasks. The other two were naive at the beginning of the experiment and were paid for their services. These three subjects had given the most reliable data in preliminary experiments. It may not be coincidental that all three played, or had played the violin.

4.2 Results and Discussion

Figure 1 shows results averaged over 3 subjects for the three different fundamentals. It plots the pitch shift as half the mean difference between the matches for corresponding positive and negative shifts. The individual subjects showed good reliability in their matches with standard errors across 5 replications of between about 0.05 and 0.2 Hz. But as in Moore's data [1] we find considerable variability between subjects in the size and shape of the pitch shift function. However, we were able to reproduce their main trends.

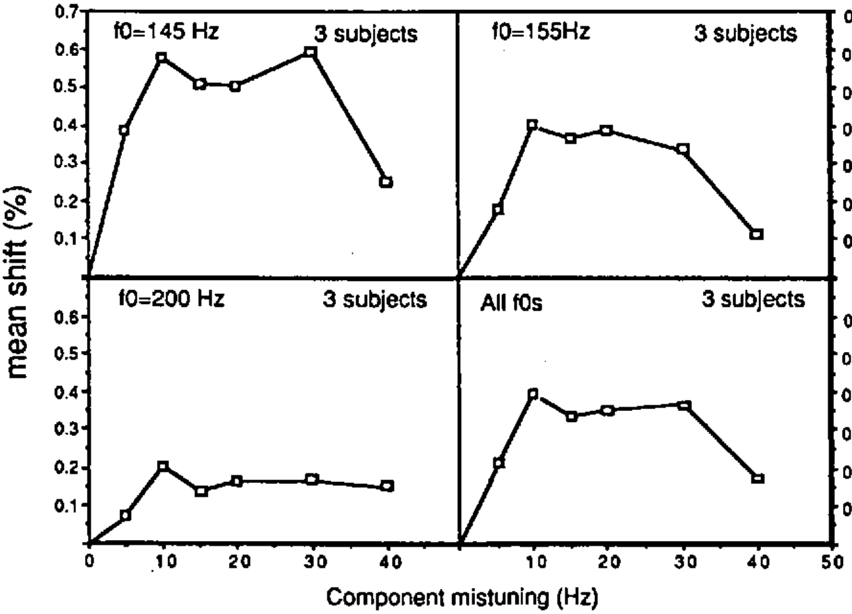

Figure 1. Mean percentage pitch shift for different absolute values of mistuning for each fundamental and their average.

Although in basic agreement with Moore's average data, a couple of differences are worth pointing out, which are comparable to differences found among Moore's individual subjects. First, the peak in pitch shift occurs slightly before Moore's 3%. Our data consistently show a value of about 10Hz as the point of maximal pitch shift corresponding to between about 1.5 and 2% of the mistuned value. Second, our data have a plateau between 12 and 30Hz (around 2 to 5%). The overall magnitude of pitch shift was around 0.4%, comparable with the 0.5% value obtained by Moore et al.

5. EXPERIMENT 2

The previous experiment has shown that our stimuli can produce detectable pitch shifts when presented singly. We now present pairs of complex sounds and examine the pitch shifts produced by mistuning a single, potentially shared partial, which has replaced a pair of harmonics that are close in frequency.

5.1 Method and stimuli
In the second experiment the same experimental paradigm was used to produce pitch matches to sounds that contained two different harmonic series, rather than a single harmonic series as in Experiment 1. The pairs of fundamentals selected were 200 + 145 Hz and 200 + 155 Hz. As shown in Figure 2 these two pairs of fundamentals have two of their harmonics (the third and fourth respectively) within about 3% of each other.

The 12-harmonic complex tones used as the basis for the first experiment were added together in appropriate pairs, but with the following change. The third harmonic of the 200-Hz fundamental and the fourth harmonics of the 145- and 155-Hz fundamentals were replaced by a single frequency ranging from roughly -8% of the lower frequency to +8% of the higher one. A total of 17 different frequency values were used for each pairing, including the two stimuli in which the variable component was in tune with one of the two fundamentals.

The two different pairings thus contained the following components:

(i) 200+145: 11 harmonics of 200 Hz (1-2, 4-12), plus 9 harmonics of 145 Hz (1-3, 5-12), plus a single 'mistuned' component whose frequency varied between 540 and 640 Hz in 17 steps.

(ii) 200+155: 11 harmonics of 200 Hz (1-2, 4-12), plus 9 harmonics of 155 Hz (1-3, 5-12), plus a single 'mistuned' component whose frequency varied between 560 and 660 Hz in 17 steps.

5.2 Procedure and subjects
Each experimental block contained one particular pairing (200+145 or 200+155). Each of the 17 different mistunings was presented 5 times giving a total of85 trials in each block. Subjects were asked to match the pitch of only one of the complex tones. Matches to the two different tones making up a pair were performed in separate experimental sessions. The period of the matching tone was constrained to be within 4% of the appropriate fundamental. This constraint allowed adequate room for bracketing the pitch, while ensuring that the subject matched the pitch of the appropriate complex. Subjects took the four blocks (2 complexes x 2 matched fundamentals) on different days. The three subjects and the details of the matching procedure were the same as in experiment

5.3 Results and Discussion
Figure 3 compares pitch matches to the two component complexes of a particular pair of sounds. The upper part of the figure shows the results for pitch matches to the 200+145 pair of complex tones, the lower part shows the corresponding data for the 200+155 pair. The figure shows the average data plotted so as to align the pitch matches made to the two stimuli when the mistuned component was actually *at its in-tune value for the fundamental being matched.*

PITCH OF SIMULTANEOUS COMPLEX TONES

Each of the curves in Figure 3 shows maximum and minimum pitch shifts at around ±3%, although the downward mistuning peaks are generally less clear than the upward ones. This finding extends to pairs of complex tones, Moore et al.'s findings for single complex tones. Our results show that a single component can contribute to the pitch of more than one complex. They also show that a component that is in a harmonic relation with one complex can still make a contribution to the pitch of another complex for which it is mistuned.

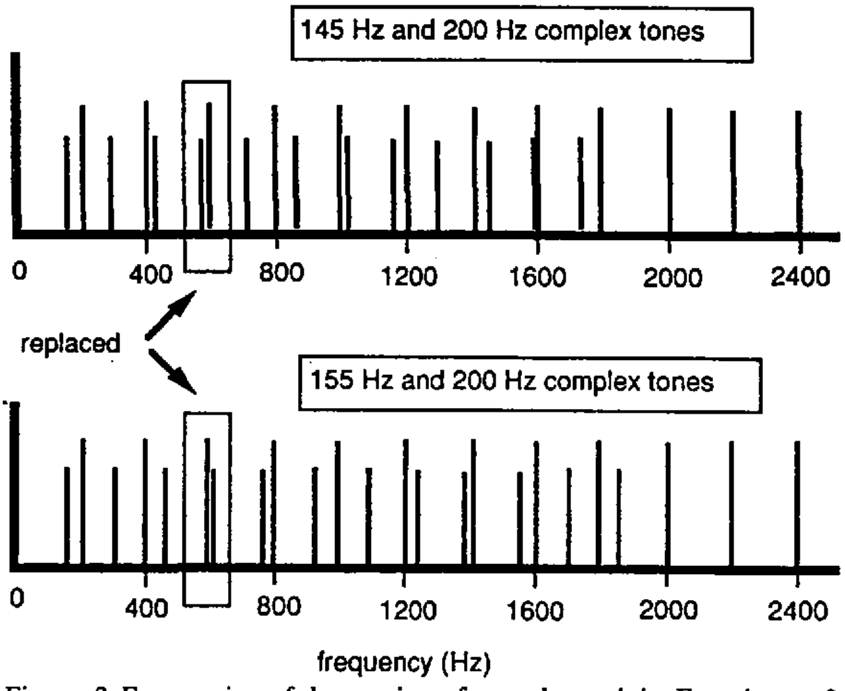

Figure 2. Frequencies of harmonics of sounds used in Experiment 2. The two components enclosed in a box were replaced by a single component of variable frequency. All components had the same amplitude - the height difference just visually separates the two harmonic series.

For instance, in the 200+145 pairing, when the variable component has a frequency of 600 Hz it is in tune with the 200-Hz series, yet produces an almost maximal positive pitch shift in the 145-Hz complex, while the 580-Hz tone produces an almost maximal negative shift in the 200-Hz complex despite being in tune with the 145-Hz series. A similar pattern is seen with the 200+155 pairing. These data are compatible with a mechanism that makes independent assessments of the pitches of simultaneous complex tones. Provided a component is within the scope of a particular harmonic series, it will contribute to its pitch, regardless of whether it is more in tune with a competing harmonic series.

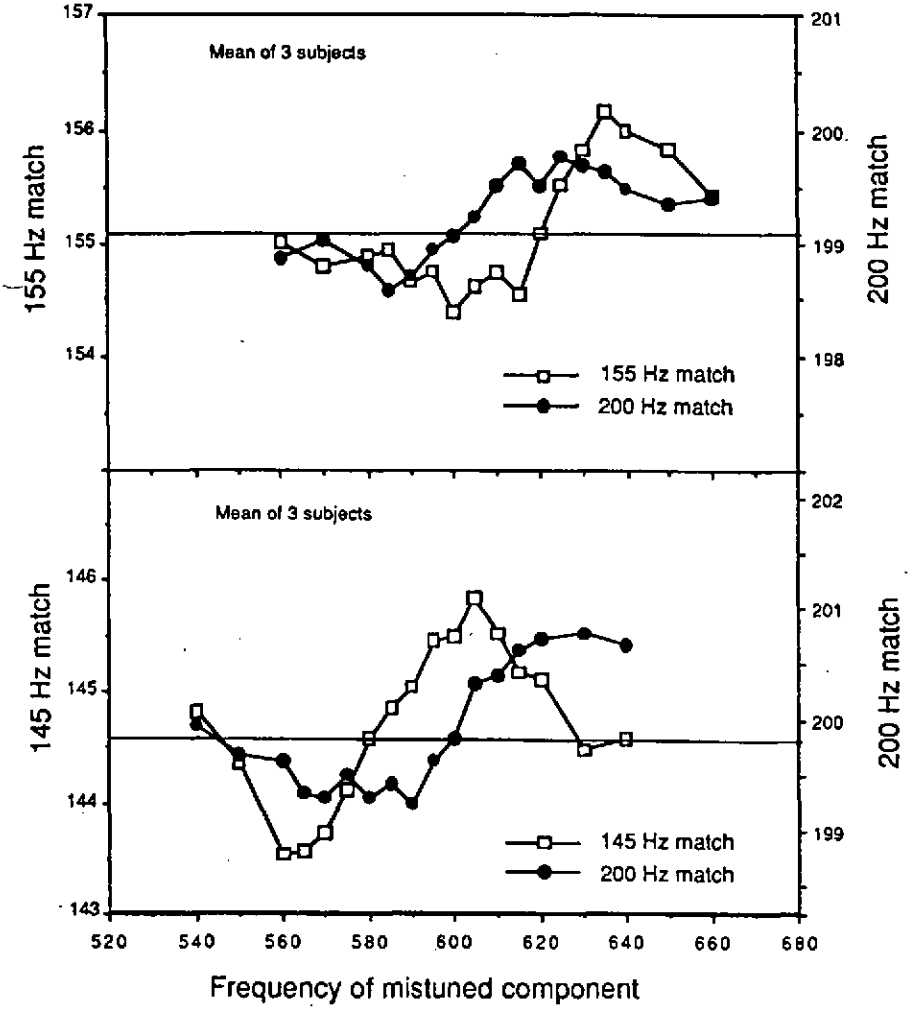

Figure 3. Mean matched fundamental frequencies averaged across three subjects, expressed as deviation from the matched value for the appropriate in-tune condition.

6. CONCLUSION

The two experiments reported here have used a pitch-matching paradigm to investigate the contribution that a single mistuned component makes to the pitch of two simultaneous complex sounds. The data show that a single mistuned harmonic can contribute to the pitch of both of two simultaneous complex sounds. The data are compatible with the pitches of each sound being determined independently, but are incompatible with the principle of 'disjoint allocation', which maintains that a particular auditory component may only make a contribution to a single auditory stream [9]. On the contrary, the results of experiment 2 provide a form of Duplex perception in which a single harmonic may make a contribution to the pitch of both of two simultaneous sounds [12, 13].

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