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Context sensitivity and invariance in perception of octave-ambiguous tones

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Abstract Three experiments investigated the influence of unambiguous (UA) context tones on the perception of octave-ambiguous (OA) tones. In Experiment 1, pairs of OA tones spanning a tritone interval were preceded by pairs of UA tones instantiating a rising or falling interval between the same pitch classes. Despite the inherent ambiguity of OA tritone pairs, most participants showed little or no priming when judging the OA tritone as rising or falling. In Experiments 2 and 3, participants compared the pitch heights of single OA and UA tones representing either the same pitch class or being a tritone apart. These judgments were strongly influenced by the pitch range of the UA tones, but only slightly by the spectral center of the OA tones. Thus, the perceived pitch height of single OA tones is context sensitive, but the perceived relative pitch height of two OA tones, as described in previous research on the "tritone paradox," is largely invariant in UA tone contexts.

Introduction

The phenomenon of multistable perception has long fascinated researchers in vision, as it can reveal endogenous determinants of perception, brain dynamics, and even neural correlates of consciousness (for reviews, see Blake & Logothetis, 2002; Leopold & Logothetis, 1999; Sterzer, Kleinschmidt, & Rees 2009). Paradigms such as ambiguous figures (e.g., face/vase, Necker cube) and binocular rivalry are familiar and widely used. Research on multistable auditory perception is much less developed because of a relative paucity of appropriate paradigms, but underlying principles may be similar in audition and vision (Pressnitzer & Hupé, 2006). One paradigm that deserves attention in that regard is the perception of octave-ambiguous tones, an invention of the 1960s.

To demonstrate that the psychological dimensions of pitch quality (chroma) and pitch height can be dissociated, Shepard (1964) ingeniously created tones that are composed of a series of partials spaced an octave apart, with the amplitude of the partials being governed by a fixed spectral envelope. These tones, which have a definite chroma but are ambiguous with regard to the octave their dominant pitch resides in, are now known as octave-ambiguous (OA) or Shepard tones. Figure 1 gives an illustration of the slightly modified OA tones used by Deutsch (1987, 1991) and in many subsequent studies, including the present investigation. They consist of six partials whose amplitudes are governed by a cosine-shaped amplitude envelope over a logarithmic frequency axis. The figure shows the partials of two tones, representing the musical pitch classes D# and A, under each of two envelopes, one centered on 262 Hz (C4) and the other centered on 370 Hz (F#4). The frequencies of the partials determine the perceived chroma or pitch class, whereas the envelope affects the perceived timbre (brightness) of these organ-like sounds. The envelope peak (or weighted mean log frequency) represents the spectral center of the tones. Tones with an envelope centered on F#4 can be said to be six semitones (st) higher than tones with an envelope centered on C4.

A set of OA tones with the same envelope, which typically includes 12 tones representing the 12 musical pitch classes, has a circular structure because all tones are in theory equally high and differ only in chroma. In the *Shepard*

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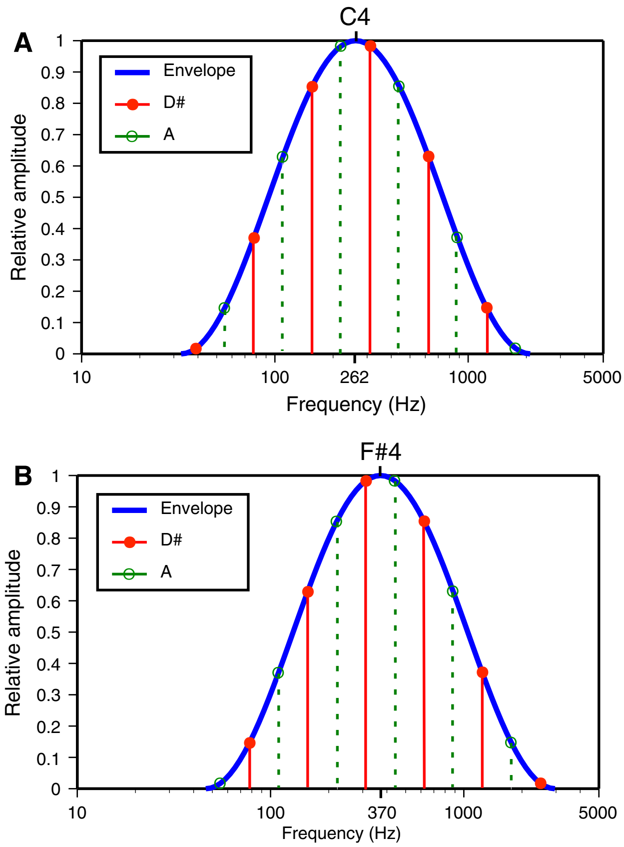

Fig. 1 Spectral structure of octave-ambiguous tones D# and A with amplitude envelopes centered on C4 (262 Hz, **a**) and on F#4 (370 Hz, **b**)

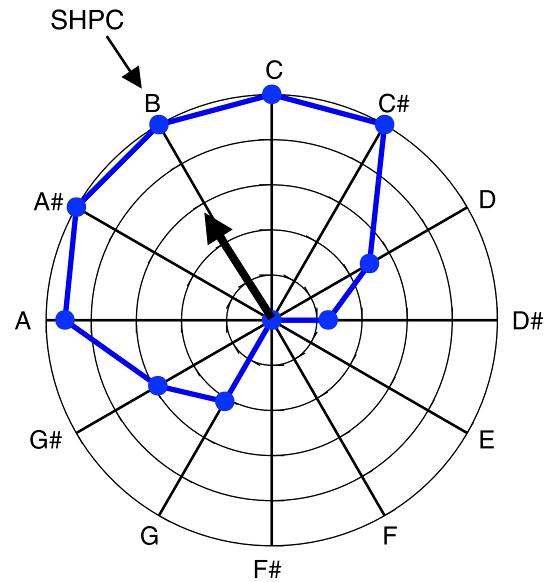

Fig. 2 Radial response graph illustrating the concept of subjectively highest pitch class (*SHPC*). Labels on the pitch class circle refer to the first tone in a tritone pair. Percentages of "falling" responses are plotted for each pair; concentric circles represent increments of 20%. The highest percentages are centered on pitch class B, which thus is the SHPC in this example. A more precise, continuously varying measure of the SHPC can be obtained by calculating the radial angle of the resultant vector of the data points (Fisher, 1993). In this example, the vector (*arrow*) points almost exactly to *B*

scale illusion, a continuous series of OA tones with the same envelope but with frequencies of partials increasing in steps of 1 st is heard by many listeners as endlessly increasing in pitch, even though the same 12 tones are repeated over and over by going around the pitch class circle. Two successive OA tones with the same envelope are generally heard as a rising interval when the pitch class of the second tone is <6 st "above" that of the first tone, and as a falling interval when the second pitch class is <6 st "below" the first (i.e., according to proximity along the circumference of the pitch class circle). However, when two OA tones span a tritone (6 st, half an octave) and thus lie opposite each other on the pitch class circle, the direction of the interval is maximally ambiguous and is heard sometimes as rising, sometimes as falling, though often with great confidence (Shepard, 1964). In this respect, OA *tritone pairs* seem somewhat analogous to perceptually bistable visual figures such as the Necker cube.

Actually, however, they represent a considerably more complex phenomenon. Given 12 OA tones having the same spectral envelope and representing the 12 pitch classes of the equal-tempered chromatic scale of Western music, there are 12 different tritone pairs, each starting with one of the pitch classes and ending with the pitch class 6 st away. Although all of these pairs are in theory equally ambiguous, Deutsch (1986, 1987) discovered that listeners tend to hear some pairs consistently as rising and others (those with the opposite order of pitch classes) consistently as falling; the remaining pairs (if any) are less consistently judged. From the pattern of individual responses to the 12 tritone pairs a subjectively highest pitch class (SHPC) can usually be inferred (see Fig. 2, explained in the caption): tritone pairs starting with that pitch class, or with one nearby, are consistently heard as falling in pitch (high response percentages in Fig. 2), whereas pairs with these tones in opposite order are consistently heard as rising (low response percentages in Fig. 2). However, which pairs are perceived most consistently as rising or falling depends very much on the listener. These findings constitute the *tritone paradox*.

It might be suggested that the tones in a tritone pair are not perceived as equally high because their individual discrete spectral envelopes (line spectra) are not identical: their most prominent partial, which constitutes the individual envelope peak, varies in both frequency and amplitude. As can be seen in Fig. 1a, among tones with an envelope centered on C4 there are some (D# and its neighbors) whose strongest partial is above C4 and others

(A and its neighbors) whose strongest partial is below C4. If the strongest partial alone determined perceived pitch height, then the SHPC of tones with a C4 envelope should be D#, whereas the SHPC of tones with an F#4 envelope (Fig. 1b) should be A. This prediction is not confirmed by data, however. In most studies of the tritone paradox, the SHPC has been nearly invariant across tone sets with different spectral envelopes (e.g., Dawe, Platt, & Welsh 1998; Deutsch, 1987, 1991; Deutsch, Kuyper, & Fisher, 1987; Giangrande, 1998), and in those studies in which the SHPC was found to change along with the envelope (Repp, 1994, 1997), the mean SHPC was not the pitch class 3 st above the envelope center but rather the one 6 st away. In all studies, moreover, there were substantial individual differences in the SHPC, which Deutsch (1991) attributed to an influence of long-term auditory experience, particularly with linguistic pitch patterns, an intriguing hypothesis that has been the subject of a number of subsequent studies (Deutsch, 1994; Deutsch, Henthorn, & Dolson 2004; Giangrande, 1998; Ragozzine & Deutsch, 1994; Repp, 1994). However, the present research is not concerned directly with this hypothesis or with the tritone paradox as such. Rather, our study uses variants of the tritone paradox paradigm to investigate whether the perception of OA tones is context dependent, or whether it is invariant.

The issue we address is of both theoretical and methodological interest. The tritone paradox rests on perceptual judgments of relative pitch height within a set of OA tones; these judgments yield an estimate of the SHPC. On one hand, individual differences in SHPC are believed to be stable because they are attributed to long-term auditory experience (Deutsch, 1991). On the other hand, we find that listeners often complain about the ambiguity of tritone pairs and feel they could hear them as either rising or falling at will. Reports of percepts of a simultaneous rise and fall in pitch, evidently caused by relationships between individual partials of successive tones, are quite common (though not well documented in the tritone paradox literature). These informal observations suggest that it should be easy to sway listeners' relative pitch judgments through instructions or contextual manipulations and thereby perhaps also to change their SHPC. We attempted to do this in Experiment 1 by preceding OA tritone pairs with tritone pairs composed of unambiguous (UA) complex tones that clearly instantiated a rising or falling interval between the same pair of pitch classes. Our expectation was that substantial positive priming would occur.

One might also ask what the perceived pitch height of individual OA tones would be relative to an unambiguous reference, and whether tones corresponding to the SHPC would be judged as relatively higher than tones from the opposite side of the pitch class circle. This is an interesting and under-researched topic. Although an OA tone exhibits octave ambiguity, all of its partials are not equally likely to coincide with its dominant perceived pitch(es). One seemingly obvious hypothesis is that the strongest partials determine the perceived pitch height of the tones. In other words, tones with envelopes centered on C4 and F#4 might be expected to be perceived, on average, as being as high as C4 (262 Hz) and F#4 (370 Hz), respectively. However, that does not appear to be the case. Terhardt, Stoll, Schermbach, and Parncutt (1986) obtained evidence that the dominant virtual pitch (i.e., the most salient of several candidate "fundamental" frequencies) of OA tones tends to be in a broad region around 300 Hz, apparently regardless of the shape of the spectral envelope. Terhardt (1991) proposed that the SHPC in the tritone paradox is due to an *internal spectral weighting function* that varies according to individuals' auditory experience, in agreement with Deutsch's (1991) similar hypothesis (see also Cohen, Grossberg, & Wyse 1995). It could then be argued that certain tones are heard as higher than others because their most strongly weighted partial is above the center of the weighting function. (Imagine that the spectral envelopes in Fig. 1 represent different internal spectral weighting functions.) Because the weighting function is internal to the listener's auditory system, it can account in principle for individual differences in SHPC. Terhardt's hypothesis suggests that it might be possible to assess the SHPC by judging the pitch heights of individual OA tones relative to UA tones. However, this immediately raises the question of whether the perceived pitch heights of individual OA tones are contextually stable. They would need to be stable in order to provide a stable estimate of the SHPC. Experiments 2 and 3 investigated these questions by using matching tasks and relative pitch judgment tasks that pitted OA and UA tones against each other.[1]

Experiment 1: priming OA tritone pairs with UA tritone pairs

Several previous studies have shown that perceptual judgment of a tritone pair composed of OA tones depends not solely on the pitch classes the pair contains and on the listener but also on preceding context of OA tones. In the standard tritone paradox paradigm, 12 different tritone pairs occur in various random orders, and it is difficult to disentangle sequential context effects from the SHPC-related fact that similar pairs tend to be judged similarly (but see the appendix in Repp, 1994, for one special case).

[1] Experiments 1 and 2 had two sub-experiments each. The chronological sequence of experiments was 1A, 2A, 3, 2B, 1B.

However, when a tritone pair is preceded by an orderly sequence of OA tone pairs that span rising or falling intervals of steadily increasing magnitude (e.g., C-C#, C-D, C-D#, C-E, C-F, C-F# vs. C-B, C-A#, C-A, C-G#, C-G, C-F#), the tritone C-F# is very likely to be perceived in accord with the preceding intervals (Giangrande, Tuller, & Kelso, 2002; Repp, 1994). Dawe et al. (1998) found that a preceding rising or falling Shepard scale can also bias perception of tritone pairs. Repp (1997) preceded each tritone pair with a single OA tone whose pitch class was halfway between the pitch classes of the tritone pair (see also Shepard, 1983). Listeners' perception of the tritone tended to minimize the total pitch range of the triplet (e.g., C-F# tended to be perceived as rising when preceded by D# but as falling when preceded by A). Repp also found that when single tritone pairs are presented out of context, on separate days, some listeners perceive nearly all pairs as rising or falling, even though they show a balanced response pattern in the standard tritone paradox paradigm. Thus, a perceptual calibration seems to occur when OA tritone pairs are presented in random order, and this calibration may well be mediated by sequential context effects.

It is currently not known whether perception of the relative pitch height of OA tones can also be influenced by a preceding context of UA tones. Considering the inherent ambiguity of OA tritone pairs, and also considering that in our experience an OA tritone pair is nearly always perceived the same way (either as rising or as falling) when it is repeated, it seems that it should be easy to prime listeners' perceptual judgments with demonstrations of clearly rising or falling intervals between the same pair of pitch classes. However, several recent studies of discretely presented visual ambiguous figures have found that, surprisingly, perception of these figures is sometimes resistant to priming by similar but disambiguated figures, whereas the percept derived from a preceding ambiguous figure tends to persevere (Braun & Pastukhov, 2007; Kanai & Verstraten, 2005; Pearson & Clifford, 2005; Sterzer & Rees, 2008). If this applies to audition as well, OA tritone pairs might be resistant to priming by UA tritone pairs. The purpose of Experiment 1 was to test these predictions. We report two separate studies, an initial experiment (Experiment 1A) and a follow-up experiment with an expanded design (Experiment 1B).

Experiment 1A: methods

Participants

Nine graduate students from the Yale School of Music (ages 22–28, 5 women), who were paid for their time, and both authors (ages 63 and 21, respectively) participated.[2] The graduate students played at least one instrument at a professional level (3 piano, 3 clarinet, 1 oboe, 1 cello, 1 harp). Both authors are active amateur musicians (BHR: piano, JMT: voice).[3]

Materials

OA tones corresponding to the 12 chromatic pitch classes were synthesized online by a program written in MAX/MSP 4.6.3 according to the specifications of Deutsch et al. (1987). Each tone consisted of six octave-spaced partials whose relative amplitudes were governed by a fixed cosine envelope centered on C4 (MIDI pitch 60, 262 Hz; see Fig. 1a). Twelve tritone pairs were created by pairing each tone with its exact opposite on the pitch class circle.

Eighteen UA tones were likewise synthesized in MAX/MSP. Each consisted of the first four harmonics of a complex tone, all at the same amplitude. This particular spectral structure was arbitrary but sufficient to ensure an unambiguous pitch percept corresponding to the fundamental frequency (the first harmonic). The tones represented MIDI pitches 46 through 63 (A#2–D#4, 117–311 Hz). This range was selected because it encompasses the peak of the spectral envelope of the OA tones as well as their presumed range of dominant pitches, according to Terhardt et al. (1986) and as judged informally by author BHR. The choice of a range of 18 st allowed the creation of two UA tritone pairs, one rising and one falling, for each pair of pitch classes. Rising pairs started on MIDI pitches 46–57 and ended on 52–63, whereas falling pairs started on 52–63 and ended on 46–57.

Each trial consisted of a UA tritone pair followed by an OA tritone pair representing the same sequence of pitch classes. Each tone was 500 ms long and of constant amplitude, except for 5 ms ramps at onset and offset to prevent clicks. There was a 1 s inter-onset interval between the two tones of each pair, and a 2 s inter-onset interval between the second tone of the UA pair and the first tone of the OA pair. The loudness levels of UA and OA tones were not matched precisely but roughly similar and comfortable. In the course of a block of 24 trials, each of the 12 OA pairs was

[2] We used musicians as participants because they happened to be readily available, being regular research participants in rhythm and timing experiments in BHR's lab.

[3] Although we are not concerned here with effects of linguistic background, we might mention that the group was very heterogeneous in that respect: It included native speakers of Cantonese (2), Mandarin (1), Korean (1), German (1), and British English (1), as well as native speakers of American or Canadian English with Chinese, Indian, or partially British parents; only two participants had a purely American linguistic background.

preceded once by a rising and once by a falling UA pair. The order of trials was semi-random. Intertrial intervals were variable (self-paced).

Equipment and procedure

The experiment was run on an Intel iMac computer, and participants listened over Sennheiser HD540 reference II earphones while interacting with programs written in MAX/MSP. (All subsequent experiments used the same equipment.) The session lasted about one hour and began and ended with a brief matching task that is described later as Experiment 2A. In between, each participant completed eight blocks of trials. Participants started each trial by clicking a button on the computer screen. The trial started after a delay of 1 s, and participants could replay it if they wished. Then they gave two responses, one for the UA pair and another for the OA pair, by clicking one of three choices ("rising," "falling," or "not sure") for each on the computer screen. After each block of 24 trials, there was a brief pause during which the data were saved and the next block was selected.

Experiment 1A: results

Participants nearly always identified the UA interval correctly as rising or falling and never gave a "not sure" response. Only four trials had incorrect responses, probably due to inattention, and we discarded those. OA pairs received a total of 11.4% "not sure" responses, each of which we counted as half a "rising" or "falling" response. We then calculated the percentage of "falling" responses for each of the 12 OA pairs when preceded by a falling UA prime and when preceded by a rising UA prime. If positive priming occurred, the mean percentage should be higher in the first case than in the second (a positive difference score). An alternative, unpredicted possibility is that of negative priming or contrast (a negative difference score).

A *t* test on the individual difference scores showed that they did not differ significantly from zero, $t(10) = 1.23$, $P = 0.247$ (two-tailed), which suggests that perception of OA pairs was not affected by the preceding UA pairs. However, this strong conclusion would be justified only if no individual participant showed any priming. We assessed the significance of individual priming effects by conducting *t* tests on difference scores calculated separately for each block of trials. Out of 11 participants, 3 (1 pianist and both authors)[4] showed significant positive priming (2 at $P < 0.001$, 1 at $P < 0.01$), 2 (1 pianist, 1 cellist) showed significant negative priming (1 at $P < 0.01$, 1 at $P < 0.05$), and 6 (1 pianist, 3 clarinetists, 1 oboist, 1 harpist) showed no reliable effects, though the pianist showed a tendency towards positive priming. Curiously, all four wind instrument players were unaffected by the primes.

The foregoing results concern only the overall response percentages and do not prove that the specific pattern of responses across the 12 tritone pairs, from which the SHPC can be inferred, was unaffected by the primes. Radial graphs of individual percentages of "falling" responses as well as the mean percentages for rising and falling primes are shown in Fig. 3. The three participants who exhibited significant positive priming and the one with a mere tendency (Pi2) are in the left column; the two participants showing significant negative priming are above the horizontal line in the center column; and the remaining participants are the ones who showed no effects. Apart from the individual differences in priming effects, which are evident in different-sized areas being enclosed by the two radial response functions, a variety of orientations of the response functions can be seen.[5] Each participant gave more "falling" responses to some OA pairs than to others, but these response patterns differed among participants, as is typically found in the tritone paradox. However, all five participants who were immune to OA context also showed similar response patterns, even though they had different language backgrounds (Mandarin, Korean, British, American).

In those participants who showed priming, the orientation of the response pattern in the pitch class circle was not changed much by different contexts. To quantify the effect of UA context on the SHPC for each participant, the angle of the resultant vector of the response percentages (see Fig. 2) was calculated for each context condition and converted into semitones relative to C (analogous to clock time in hours). These results are shown in columns 2 and 3 of Table 1. The largest individual shift as a function of UA context was 1.54 st (Pi2), and 9 of 11 participants showed shifts of less than 1 st. The shift in the mean SHPC was 0.16 st, and the linear correlation between the individual resultant vector angles in the two priming contexts was 0.97. Thus, the SHPC was basically unaffected by different primes.

Because the axis labels in Fig. 3 represent the first pitch class in the OA pair, the SHPC of each participant is at the center of the peak region of "falling" responses. This pitch class (or pair of pitch classes, in the case of a near tie) is also indicated for each participant in Table 1. On average, it

[4] Both authors also had shown positive priming in an earlier pilot run.

[5] One participant (JMT) gave predominantly "falling" responses, whereas two (Ce, Cl1) gave predominantly "rising" responses. Such strong biases towards one or another response are rarely found in the tritone paradox. By intervening between successive OA pairs, the UA pairs may have reduced sequential context effects among OA pairs and thereby disrupted the perceptual calibration that usually occurs during exposure to a set of OA tones.

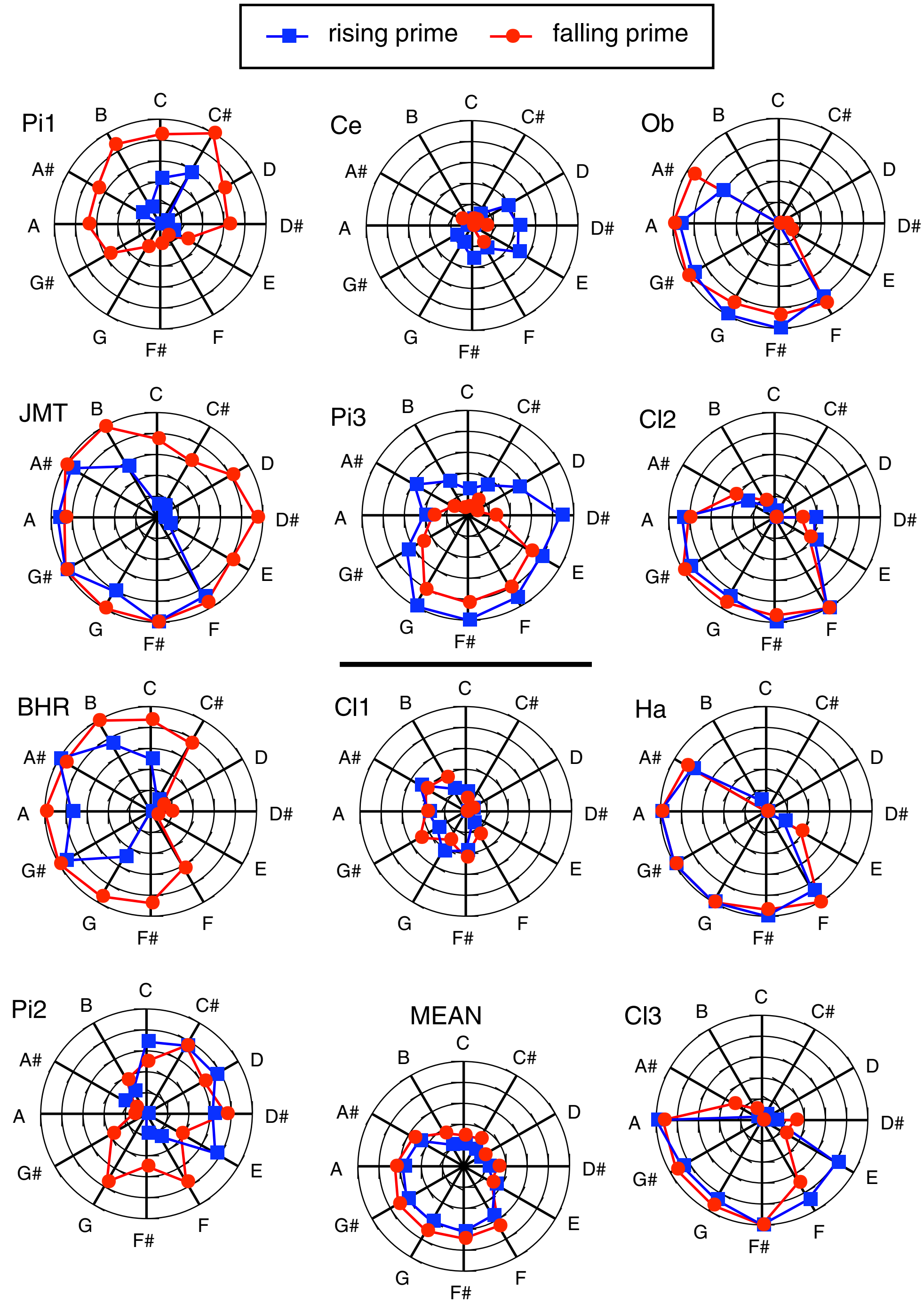

Fig. 3 Experiment 1A: percentages of "falling" responses to individual OA tritone probe pairs when preceded by rising and falling UA primes, for 11 individual participants and the mean. Pitch class labels refer to the first tone in tritone pairs. Radial axes go from 0 to 100% in 20% steps. Participants are identified by their instrument (*Pi* piano, *Ce* cello, *Cl* clarinet, *Ob* oboe, *Ha* harp), the authors by initials (BHR, JMT)

was G and/or G#, a pattern shared by the five participants who showed no priming effect and also by one (JMT) who showed positive priming. The remaining participants had different SHPCs. There is no obvious explanation for these individual differences in terms of the participants' language backgrounds.[6]

[6] Although only one participant (Cl2) was a native speaker of British English, the average pattern curiously resembles that found previously with Southern British listeners (Deutsch, 1991) and also with a linguistically heterogeneous group of students in Canada (Dawe et al., 1998).

Experiment 1B: rationale

The surprising result of immunity to priming in a number of participants and the somewhat limited design of Experiment 1A led us to conduct a second experiment with an expanded design, one change in method, and partially different participants. First, Experiment 1B included a no-context baseline condition, because it could be that UA primes, regardless of whether they are rising or falling, change the SHPC relative to the standard tritone paradox condition in which OA pairs follow immediately upon each other. Second, we employed

Table 1 Individual results from three experiments

Ptcpt	Experiment 1A		Experiment 2A		Experiment 3	
	Rising prime	Falling prime	Highest PC	Mean pitch	Low range	High range
Pi1	0.27 (C)	−0.24 (C)	7.19 (G)	55.9 (G#3)	51 (D#3)	54 (F#3)
JMT	7.83 (G#)	7.42 (G/G#)	2.76 (D#)	58.3 (A#3)	57 (A3)	60 (C4)
BHR	9.53 (A/A#)	9.12 (A)	10.85 (B)	51.6 (D#3/E3)	54 (F#3)	57 (A3)
Pi2	1.95 (D)	3.49 (D#/E)	−1.68 (A#)	56.6 (G#3/A3)	56 (G#3)	58 (A#3)
Ce	4.09 (E)	2.78 (D#)	3.82 (E)	60.0 (C4)	58 (A#3)	64 (E4)
Pi3	5.56 (F/F#)	5.98 (F#)	8.09 (G#)	56.9 (A3)	51 (D#3)	59 (B3)
Cl1	8.52 (G#/A)	8.35 (G#)	11.26 (B)	52.8 (F3)	–	65 (F4)
Ob	7.37 (G)	7.51 (G/G#)	3.91 (E)	55.8 (G#3)	54 (F#3)	55 (G3)
Cl2	6.73 (G)	6.93 (G)	7.81 (G#)	58.0 (A#3)	–	65 (F4)
Ha	7.44 (G/G#)	7.27 (G)	6.69 (G)	59.0 (B3)	–	65 (F4)
Cl3	6.54 (G)	7.05 (G)	11.67 (C)	47.5 (B2/C3)	–	64 (E4)
Mean	7.26 (G)	7.42 (G/G#)	8.29 (G#)	56.1 (G#3)		

Columns 2–4: mean resultant angle of radial response graphs (Figs. 3, 6) converted into semitone distance from C, and nearest pitch class(es) (PC). Column 5: mean MIDI pitch of all matches and nearest musical pitch(es). Columns 6 and 7: MIDI pitch (rounded) and musical pitch of 50% crossover of individual response functions (Fig. 9)

two different sets of OA tones with different spectral envelopes. This gave us an opportunity to re-investigate the effect of envelope center on the SHPC, a contentious issue in the past, and also to examine whether priming differs across envelope sets. Third, we used two different pitch ranges of UA tones as primes because it could be that the UA primes in Experiment 1A were ineffective because they were not well matched to the dominant pitches of the OA tones. Also, UA pitch range might have an effect on the SHPC of OA tones, which would be interesting to know. Finally, we changed the kinds of responses given by participants: instead of judging both UA and OA tone pairs as rising or falling, they judged whether the two pairs represented pitch changes in the same direction or in different directions. This made the purpose of the experiment less transparent, and because we could be confident that the UA tone pair would be perceived as intended we could infer from the responses how the OA pair was perceived.

Experiment 1B: methods

Participants

Five participants (Pi3, Cl2, Ha, BHR, JMT) were the same as in Experiment 1A. Five additional paid musicians participated, including 1 pianist/composer, 1 violinist, 1 violist, 1 double bassist, and 1 bassoonist. Altogether there were 6 women and 4 men, and ages ranged from 22 to 29, except for BHR who was 64.[7]

[7] Linguistic backgrounds were now as follows: Mandarin (2), Cantonese (1), Korean (1), German (1), British (2), American (3).

Materials

We synthesized two sets of OA tones, with envelopes centered on C4 (as in Experiment 1A) and F#4, respectively (as shown in Fig. 1), and two sets of UA tones, one with MIDI pitches ranging from 46 to 63 (low range; as in Experiment 1A) and the other with pitches ranging from 52 to 69 (high range). The two ranges thus represented a relative shift of 6 st, just like the two envelope centers. Each set of OA tones was combined with each set of UA primes, which yielded four conditions. Conditions in which OA tones with the same envelope were combined with UA primes from different ranges shared half their UA–OA pairs (6 with rising primes, 6 with falling primes), whereas the other half of the pairs had UA primes that were an octave higher in the high range than in the low range.

Procedure

Participants came for two sessions on different days. In each session, envelope was constant; some participants were assigned the C4 envelope in the first session, others the F#4 envelope. Each session had three parts: a baseline condition (no primes) followed by two priming conditions (low and high ranges of UA primes). The order of the two priming conditions was counterbalanced across participants. In each condition, participants listened to 6 blocks of 24 trials each. The semi-random order of the trials was the same in all six conditions, to rule out any differences due to sequential effects among the OA tone pairs. The timing of the tones within each trial was the same as in Experiment 1A. In the baseline condition, the timing of OA pairs was approximately the same as in the priming conditions; that is, there was silence instead of a UA prime, though trials were self-paced. Participants chose from the responses "rising," "falling," and "not sure" in the baseline condition. In the priming conditions, participants chose from the responses "same," "different," and "not sure," which referred to the directions of the UA and OA tritone intervals in a trial.

Experiment 1B: results

The mean percentage of "not sure" responses across all conditions was 11.9%.[8] The percentage was larger (16.6%) for OA tones with the C4 envelope than for those with the F#4 envelope (7.2%), $t(9) = 2.40$, $P = 0.040$. There were large individual differences, ranging from hardly any "not sure" responses to nearly 50%. We again counted each such response as half a "falling" response.

Percentages of implicit "falling" responses to OA tone pairs in the priming conditions were obtained by considering "same" responses when the UA prime was falling but "different" responses when the UA prime was rising. Here the results of author BHR presented an unexpected anomaly: although he again showed positive priming, as in Experiment 1A, he perceived the OA pairs with the C4 envelope almost always as rising in both priming conditions, though not in the baseline condition. Because no other participant showed any similar pattern, it seemed prudent to exclude BHR's data from further analyses. The cause of the radical difference in his responses compared to the identical stimuli in Experiment 1A (Fig. 3) remains unclear.

A repeated measures ANOVA with the variables of envelope (C4, F#4), prime direction (rising, falling), and UA pitch range (high, low) was conducted on the overall percentages of "falling" responses in the priming conditions. There was only one effect that approached significance, namely the main effect of prime direction, $F(1,8) = 5.19$, $P = 0.052$. It reflected a weak overall tendency toward positive priming. We did not conduct significance tests on individual data in this experiment. Clearly, only some participants showed positive priming; others showed hardly any priming or even a negative tendency.

The average response patterns in all conditions, including the baselines, are shown in Fig. 4. First, it can be seen that the overall positive priming effect was small and more pronounced with the C4 envelope than with the F#4 envelope, though that interaction was not significant. Second, as the ANOVA suggested, there was no effect of UA pitch range on priming. Third, it is evident that there was little change in response pattern between baseline and priming conditions, apart from BHR's excluded results. This means the SHPC was not affected by priming or the presence of priming stimuli.

Two further results do not concern priming but the effect of envelope on the response distributions. First, it is evident that there was greater response uncertainty with the C4 envelope than with the F#4 envelope. Indeed, the mean results obtained with the F#4 envelope are nearly categorical, with half the OA pairs being judged as falling and the other half as rising. This means that individual differences in tritone perception were minimal with the F#4 envelope; all participants basically had the same SHPC. Second, the SHPCs suggested by the response patterns for the two envelopes are similar, the difference being about 1 st. The response pattern obtained with the C4 envelope is very similar to that of Experiment 1A, suggesting mean SHPCs of G#/G, whereas the response pattern for the F#4 envelope suggests SHPCs of A/G#. We did not conduct detailed analyses of individual SHPCs in this experiment because the foregoing qualitative observations suffice for our purpose.

Discussion

Contrary to what one might have expected given the theoretical ambiguity of all OA tritone pairs and the manifest ambiguity of at least some pairs for some listeners, OA tritone perception was not easily swayed by UA primes. Only some participants exhibited a positive priming effect, whereas others showed no effect or even a contrast effect. This result suggests that perception of the relative pitch height of OA tones is governed to a large extent by internal perceptual criteria that are resistant to contextual bias, consistent with the claim that the SHPC is determined primarily by long-term auditory experience (Deutsch, 1991; Terhardt, 1991). The finding also seems consistent with results from vision research showing little or no priming of ambiguous figures by unambiguous figures under certain conditions (Braun & Pastukhov, 2007; Kanai & Verstraten, 2005; Pearson & Clifford, 2005; Sterzer & Rees, 2008). It is possible that in audition, too, percepts derived from ambiguous and unambiguous stimuli are processed in different neural circuits. However, the fact that some individual participants did show substantial priming effects weakens this parallel.

The observed individual priming effects were most likely perceptual, not just a response bias. For example, author BHR hardly ever perceived any ambiguity in OA pairs, being a strongly "synthetic" listener (cf. Houtsma & Fleuren, 1991), yet showed reliable positive priming. Among other participants, some of those with high percentages of "not sure" responses, who often heard rising and

[8] A few responses that failed to register were also treated as "not sure" responses.

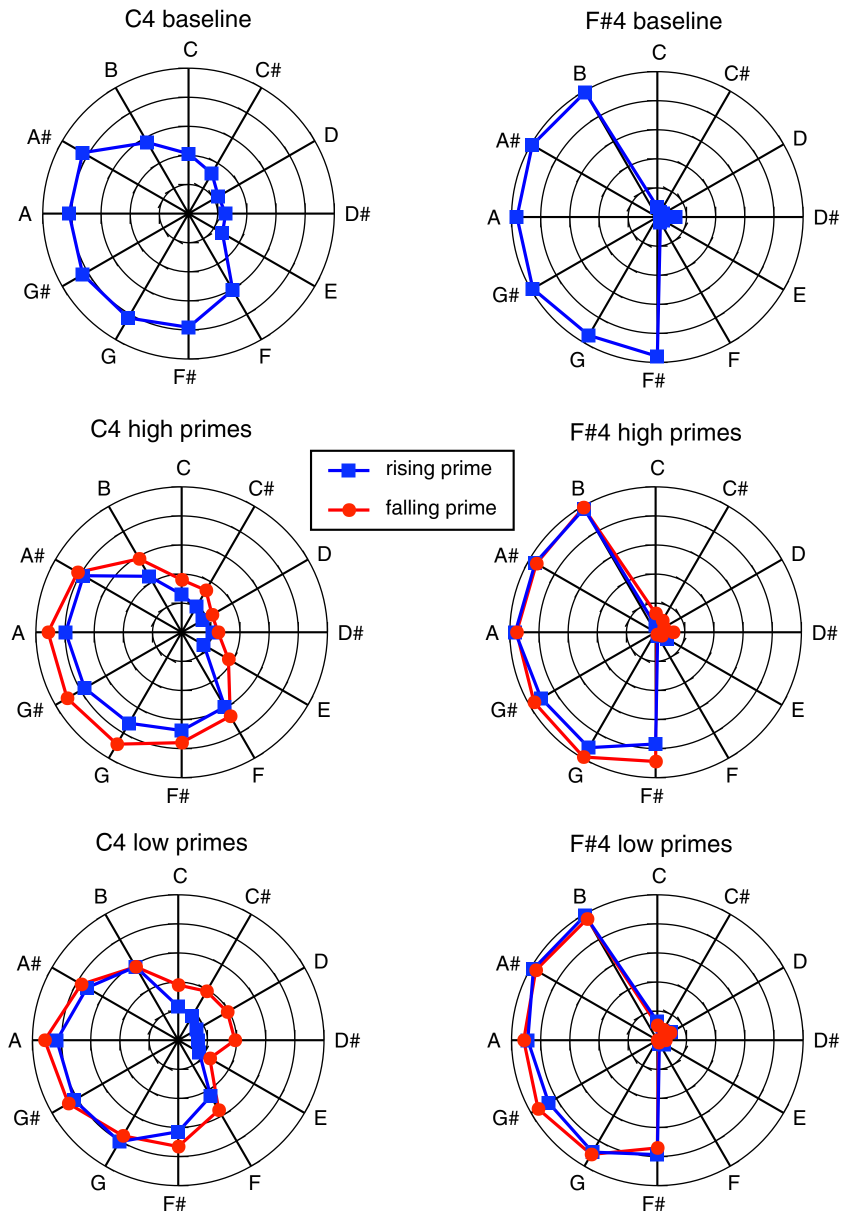

Fig. 4 Experiment 1B: mean percentages of "falling" responses in baseline and priming conditions

falling pitches of different harmonics simultaneously ("analytic" listeners; Houtsma & Fleuren, 1991) and thus should have been most susceptible to response bias, showed no priming at all, which suggests that response bias was not prevalent. Moreover, response bias cannot easily account for contrast effects. However, we still do not know why some individuals show priming while others do not.

The present results do not replicate the reversal of the mean SHPC found by Repp (1997) with different OA tone envelopes, separated by 6 st. Here the envelope center had only a small effect on the SHPC, as in previous studies by Deutsch (1987, 1991; Deutsch et al., 1987) and others (Dawe et al., 1998; Giangrande, 1998). The reason for this difference from previous results obtained in the same laboratory, even using the same headphones, is not known. The envelopes in Repp's earlier experiments were centered on different, higher pitches, but it is unclear why that should have been critical with regard to the SHPC, as similar envelopes were also used by Deutsch and others.

One quite unexpected finding was the absence of individual differences in perception of OA tritone pairs with an F#4 envelope. Although lesser ambiguity of OA tones with an F#4 envelope than of tones with a C4 envelope has been noted previously (Giangrande, 1998), the only precedent for such uniformity in OA tone perception is Repp's (1994) study, where he found no variation in perception of tritone pairs formed from original Shepard tones (with 10 partials) with an envelope centered on D#3, and also a limited range of individual differences for pairs of tones with an A4 envelope (and 6 partials). By contrast, Giangrande (1998) reported SHPC distributions for tones generated under four different envelopes that show substantial individual differences with F#4 and F#5 envelopes, though even greater differences with C4 and C5 envelopes. Moreover, in that study the most frequent SHPCs with the F#4 envelope were C and C#, whereas in the present study the mean SHPCs were G#/A, a difference of 4 st. The present results are similar to those reported for native speakers of Southern British English (Deutsch, 1991), although only one participant belonged to that group. Thus, there are still many unsolved puzzles in connection with the tritone paradox.

Experiment 2: matching OA tones with UA tones

The main result of Experiment 1 is that the perceived relative pitch height of OA tones in tritone pairs is fairly resistant to bias by a context of UA primes. What could provide the internal criteria on which the context independent perceptual judgment of OA tritone pairs is based? One possibility is that a SHPC is specified abstractly, based perhaps on language experience (Deutsch, 1991; Deutsch, Henthorn, & Dolson, 2004)—a form of implicit absolute pitch. Judgments would then be made based on the pitch classes of the OA tones relative to the internally represented SHPC, and it would not be necessary that individual OA tones actually differ in perceived pitch height. In other words, tones might only *seem* to be judged as being different in height when in fact they are perceived to be equally high and are judged based on pitch class. This is essentially the view associated with Diana Deutsch. An alternative possibility is that individual OA tones do differ in perceived height, despite their fixed spectral envelope. A possible mechanism for this is the internal spectral weighting function proposed by Terhardt (1991) and also by Cohen et al. (1995): if the weighting function peaks in a certain frequency region, and if the spectral component with the strongest weight is most likely to be perceived as the dominant virtual pitch, then OA tones having their strongest partial above the peak of the weighting function will tend to be heard as higher than OA tones that have their strongest partial below the peak. If that were the case, and if the internal weighting function is contextually stable, it might be possible to assess the SHPC by determining the perceived pitch height of individual OA tones against a UA pitch reference. Experiments 2 and 3 explored this possibility.

Ragozzine (2001) conducted an experiment in which he presented single OA tones and asked participants to judge whether they were the first tone of a potentially rising or falling tritone pair. Participants could do this, but only if they had previously been exposed to a series of OA tritone pairs. However, this is not exactly what we are after because the judgments basically still concerned relative pitch height of OA tones (i.e., relative to a memory reference of pitch range or average pitch height derived from exposure to a set of OA tones) and resembled judgments of complete OA tritone pairs.

The only study we know in which individual OA tones were compared with UA tones was conducted by Terhardt et al. (1986). They asked participants to adjust a pure-tone oscillator to the frequency that corresponded to the perceived dominant virtual pitch of OA tones. The tones had eight octave-spaced partials and rectangular or sloping (equal loudness) spectral envelopes, unlike typical Shepard tones. Across a number of participants and repetitions, each tone elicited pure-tone matches in several octaves, but not with equal likelihood: the overall distribution of matches peaked in the vicinity of 300 Hz, regardless of envelope. This result was also predicted approximately by a model of pitch perception that derives several virtual pitches of different salience from the spectrum of any complex tone (Terhardt, Stoll, & Seewann, 1982a, b). Terhardt (1991) used these modeling results to explain the SHPC in the tritone paradox, as described in "Introduction" (see also Cohen et al., 1995).

The method of matching pure tones to perceived virtual pitches has the potential drawback of drawing undue attention to individual partials of the OA tones (spectral pitches, in Terhardt's terminology). Although Terhardt et al. (1986) instructed participants to match virtual, not spectral pitches, the distinction becomes unclear if analytic listening is encouraged by the paradigm. In a pure tone, there is no distinction between spectral and virtual pitch. Therefore, we chose instead to ask participants to match the virtual pitch of UA complex harmonic tones (corresponding to their fundamental frequency) to the perceived dominant virtual pitch of OA tones. Complex harmonic tones tend to be perceived synthetically, so that the physical match of their fundamental frequency with one of the partials of the OA tones should be less obvious. We also thought that OA tones with bell-shaped spectral envelopes might have a narrower region of salient virtual pitches than the broad-envelope OA tones investigated by Terhardt et al. (1986).

We conducted two matching experiments. In Experiment 2A, we were interested primarily in confirming the distribution of pitch matches reported by Terhardt et al. (1986). However, we also wondered whether the results of the matching task would reveal differences in perceived pitch height among individual OA tones that correspond to the SHPCs found for the same participants in Experiment 1A. If a significant relationship were found, the pitch matching task might constitute a possible alternative method to the standard tritone paradox paradigm for assessing individual differences in SHPC.

In Experiment 2B, we used a modified matching procedure and compared results for two sets of OA tones with different spectral envelopes. Terhardt et al. (1986) did not find any effects of spectral envelope, which could be taken to suggest that the dominant pitch of OA tones depends entirely on an internal weighting function and not on the physical structure of the sound. However, that cannot literally be true, and Terhardt et al. did not vary the envelope center while keeping the envelope shape invariant. It seems more likely that perception of pitch height would depend both on sound structure and internal weighting. A hypothesis based only on spectral sound structure would predict that OA tones with an F#4 envelope should be perceived as 6 st higher than tones with a C4 envelope.

Experiment 2A: methods

Participants

The participants were the same as in Experiment 1A.

Materials

The OA (with C4 envelope) and UA tones were the same as in Experiment 1A, but the pitch range of UA tones was wider, extending from C2 (65 Hz, MIDI pitch 36) to B5 (988 Hz, MIDI pitch 83).

Procedure

Experiment 2A was performed at the beginning of the session of Experiment 1A and repeated at the end of the session. The computer screen showed a small four-octave piano keyboard template on which UA tones could be played by clicking on the keys. A single OA tone could be played by clicking on a separate button. Participants were presented with the 12 OA tones one by one, in random order. For each tone, they were asked to find the best match among the UA tones of the same pitch class. They could play the OA tone and the four possible UA comparison tones as often as they wished. Once they had selected a best match, they answered two additional questions on the screen: whether any other tone matched equally well (to which they could answer yes, perhaps, or no), and whether that other tone was one octave higher or lower than the chosen tone.

Experiment 2A: results

We counted each primary match and each confident secondary match as a full response, and a less confident secondary match ("perhaps") as half a response. The response distributions for the first and second runs of the matching test were similar, so we combined them. Figure 5 shows a frequency histogram of all responses. It is distinctly

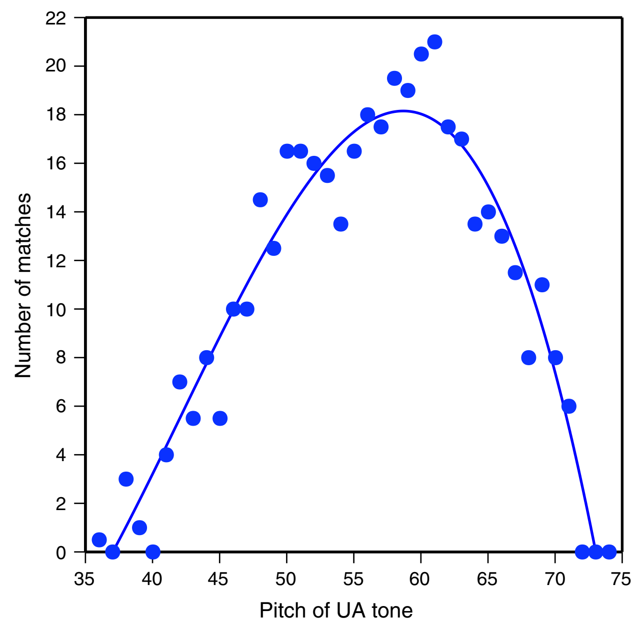

Fig. 5 Experiment 2A: frequency histogram of MIDI pitches of UA tones chosen as matches for OA tones, for all OA tones combined. The function fitted to the data is a cubic polynomial

unimodal and slightly skewed towards higher frequencies. It covers a three-octave range (MIDI pitches 36–72, C2–C5) and has its peak in the vicinity of C4 (262 Hz, MIDI pitch 60), which happens to be the center of the spectral envelope of the OA tones, though this may be coincidental. There were no responses above C5, even though the range of UA tones extended to B5. (Note that the right end of the *x* axis in Fig. 5 has been truncated.)

To compare individual response patterns, we calculated a subjective pitch height estimate for each OA tone and for each participant by taking the MIDI pitch number of the primary UA match and then adding or subtracting 6 st for a confident secondary match (i.e., averaging the MIDI pitch numbers of the two matches) or 3 st for a less confident secondary match (amounting to a weighted average). For example, if for the OA tone C the UA tone C4 (MIDI pitch 60) was selected as the primary match and C5 (MIDI pitch 72) was selected as a confident secondary match, the estimated pitch height of the OA tone was 66. We averaged the estimates from the two runs and smoothed them with a 3-point averaging window going around the pitch class circle. Figure 6 plots the resulting estimates in radial graphs for all individual participants and the mean. The arrangement of participants is the same as in Fig. 3. The axes of the graphs have been scaled to the range of the individual data: the larger the distance between the concentric circles (a step size of 2 st), the narrower is the range of perceived pitch heights, and the smaller and probably less reliable are the perceived height differences among OA pitch classes. (The data were too sparse for statistical tests.)

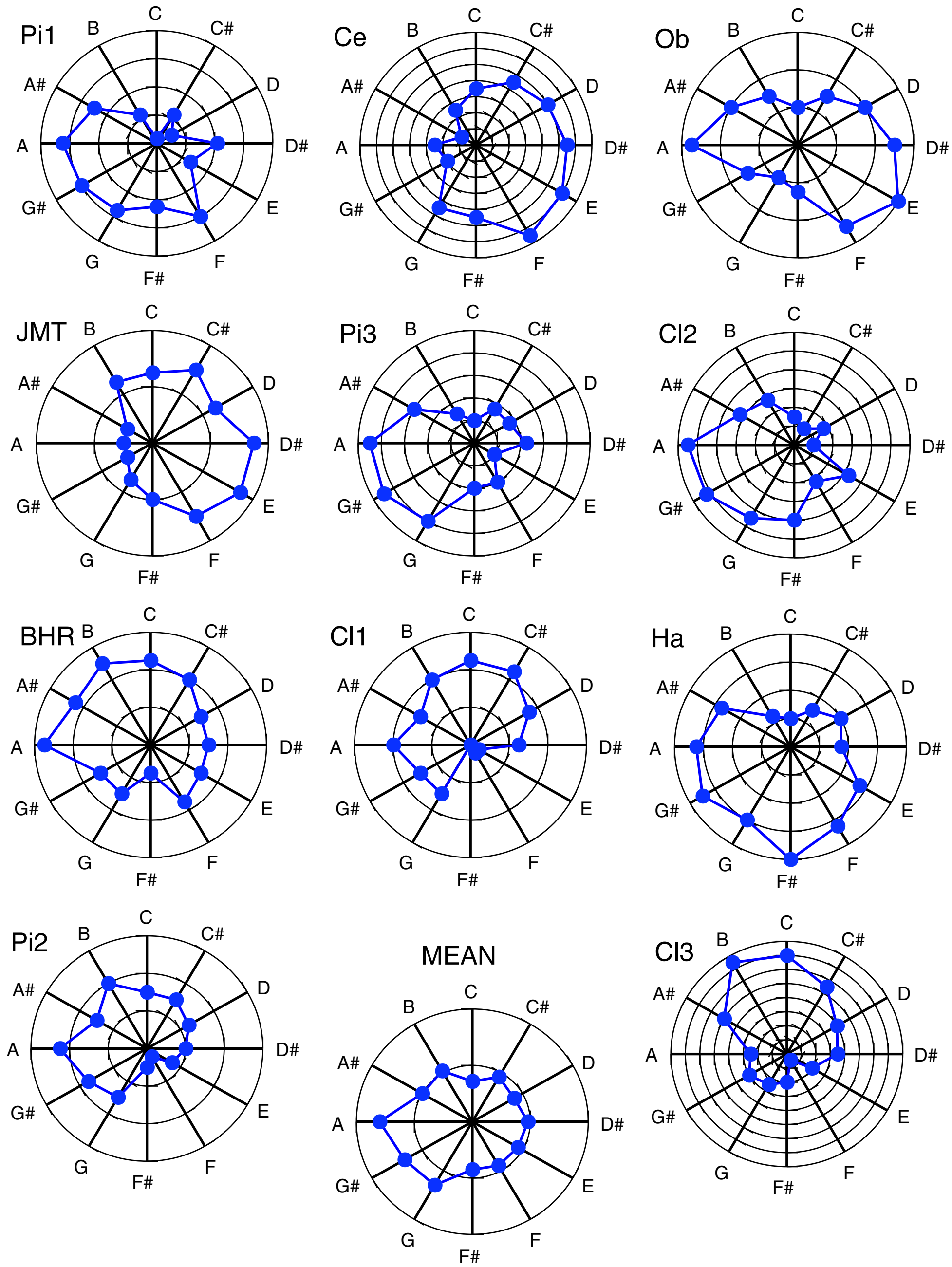

Fig. 6 Experiment 2A: mean subjective pitch height estimates of OA tones derived from the matching task, for 11 individual participants and the mean (labels and arrangement as in Fig. 3). The radial axes of each graph are scaled to the range of the data; the step size is 2 st. Pitch class labels refer to individual OA tones

The mean estimates show a tendency for pitch classes G, G#, and A to be subjectively higher than the others, which is consistent with the mean SHPC in Experiment 1A (Fig. 3); the mean resultant vector angles in the two experiments differ only by about 1 st. However, the trend is quite small, amounting to a mean difference in subjective pitch height of only about 1 st between subjectively high and low OA tones. Moreover, there is little agreement between experiments at the individual level, as can be seen in Table 1 (column 4). Only a few of the individual SHPCs (for BHR, Ce, Cl2, Ha) resemble those in Experiment 1, with a difference of less than 2 st. Other SHPCs are radically different, even in the case of individuals whose pitch matches cover a wide range and thus are presumably more reliable than others (Pi3, Cl3).

The mean of each participant's pitch height estimates is also shown in Table 1 (column 5). The means range from 47.5 (B2/C3) to 60 (C4), with a grand mean of 56.1 (G#3). Thus, there were individual differences in the mean absolute perceived pitch height of the OA tones, but these differences bear no obvious relation to the results of Experiment 1A.

To our surprise, several participants mentioned that they wished they had been able to select as their secondary choice a UA tone *two* octaves higher or lower than the primary choice (skipping the tone in the octave in between). This observation motivated Experiment 2B.

Experiment 2B: methods

Participants

The participants in Experiment 2B were the same as in Experiment 1B plus one additional musician, a violinist.

Materials

Experiment 2B used two sets of OA tones, with spectral envelopes centered on C4 and F#4 respectively, as in Experiment 1B. UA tones ranged from C1 (33 Hz, MIDI pitch 24) to B5 (988 Hz, MIDI pitch 83).

Procedure

Experiment 2B was performed at the beginning and end of an experimental session that was unrelated to the present study and did not use similar materials. One run used the OA tones with the C4 envelope, and the other run used the tones with the F#4 envelope, with the order counterbalanced across participants. As in Experiment 2A, the OA tones were presented singly in random order and could be listened to repeatedly by clicking a button. For each OA tone there were five UA comparison tones from different octaves, which could be played repeatedly by clicking on five buttons. The task was to assign each comparison tone a rating between 1 and 5 that reflected how well it matched the perceived dominant pitch of the OA tone. It was permitted to give the same rating to more than one comparison tone.

Experiment 2B: results

Some participants indeed gave ratings in this experiment indicating that UA tones two octaves apart matched an OA tone better than did the UA tone in the octave in between. However, the surprising main result of this experiment eradicates any concern with detailed response patterns. For each OA tone and each participant, we calculated a weighted mean subjective pitch height from the MIDI pitch numbers of the five UA comparison tones, using the ratings as weights. These data are plotted in Fig. 7 as a function of OA pitch class.

The data are plotted on a linear (semitone) rather than a circular scale because, remarkably and quite unexpectedly, the subjective pitch height of OA tones increased steeply and linearly from C to B, $F(11,110) = 52.53$, $P < 0.001$. This effect was shown by all participants and was clearly related to the fact that the mean pitch of the five UA comparison tones in the test increased linearly from C to B. Although the choice of C as the lowest pitch class was arbitrary, the pitches of the five UA comparison tones necessarily had to increase with the pitch class of the OA tone. The mean increase in judged pitch height from C to B was about 8 st, compared to an increase of 11 st in the mean pitch height of UA comparison tones. The range of mean pitch heights (roughly, MIDI pitches 50–60, or D3–C4) is slightly below the peak of the response distribution in Experiment 2A but basically consistent with it.

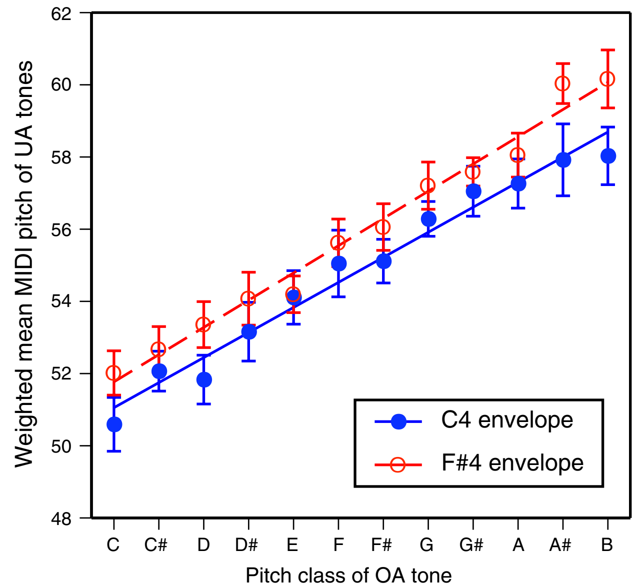

Fig. 7 Experiment 2B: mean subjective pitch heights (weighted mean of MIDI pitches of UA comparison tones) of OA tones with two different spectral envelope centers (C4 and F#4)

In addition, Fig. 7 shows that the spectral envelope of the OA tones had but a small effect on judged pitch height: OA tones with an F#4 envelope were perceived as being only about 1 st higher than OA tones with a C4 envelope. This effect was significant, $F(1,10) = 9.64$, $P = 0.011$, and did not interact with pitch class.

Because of the unexpected strong dependency of the subjective pitch height of OA tones on the mean pitch height of the UA comparison tones, it was not possible to infer any SHPC from these data.

Discussion

The overall distribution of pitch matches in Experiment 2A, with its mode near 260 Hz, is consistent with, though slightly lower than, the distribution obtained by Terhardt et al. (1986). Although it might be argued that this distribution simply reflects the spectral energy in tones with a C4 envelope, it should be remembered that Terhardt et al. found no systematic effect of varying the spectral envelope. Also, the results of Experiment 2B suggest that a 6-st shift in spectral envelope has only a small (1-st) effect on the subjective pitch height of OA tones. This result is consistent with the hypothesis that the dominant virtual pitch is determined primarily by an internal spectral weighting function, not by the objective spectral height of the tones. It is well known that the dominant virtual pitch of a harmonic complex tone, which usually corresponds to the fundamental frequency, can still be perceived when the sound is band-pass filtered so that only several higher harmonics remain (e.g., Schouten, Ritsma, & Cardozo, 1962). Also, tones with a higher spectrum (brighter timbre) can be perceived as having a lower pitch than sounds with a lower spectrum (Seither-Preisler et al., 2007). Similarly, the dominant virtual pitch of OA tones need not reflect the spectral energy distribution directly.

The response distribution in Experiment 2A, which ranges roughly from 60 to 500 Hz, is narrower than that found by Terhardt et al. (1986), which ranged from 125 to 2,000 Hz. This may be due in part to the convex spectral envelope of our OA tones, which concentrated spectral energy in a narrower region (assuming that gross characteristics of the spectral envelope do have some impact on pitch height judgments). In addition, the pure comparison tones of Terhardt et al. may have encouraged matches to individual partials (spectral pitches), despite instructions to focus attention on virtual pitches. Our method of using complex harmonic comparison tones may have been more successful in restricting matches to the virtual pitches of the OA tones.[9]

Even though Experiments 2A and 2B differed by only a minor change in procedure, their results were radically different. In Experiment 2A, participants played comparison UA tones by clicking on a horizontal miniature keyboard, whereas in Experiment 2B they played them by clicking on vertically arrayed buttons, which seems unlikely as a cause of the difference in results. In both experiments, the mean pitch height of the available comparison tones increased from C to B, and participants could play both OA and UA tones as often as they liked. The crucial difference may have been that in Experiment 2A participants were not obliged to listen to all UA comparison tones; they could select a best match by just focusing on the most likely candidate(s) and ignoring other choices. In Experiment 2B, however, they had to listen to each tone at least once in order to give it a rating (at least they had been instructed to do so), and perhaps they did listen to each UA tone just once, whereas in Experiment 2A they may have played the preferred UA candidate tones repeatedly. Whatever the case may have been, a small difference in procedure brought about a strong context dependency of the subjective pitch height of the OA tones. It could also be argued that participants in Experiment 2B were simply lazy and gave the same ratings to the five comparison tones for each OA tone. However, in that case the subjective pitch height of the OA tones should have increased by 11 st from C to B, whereas in fact it increased only by 8 st. Thus, the pitch range of the UA comparison tones was not the only determinant of participants' ratings, though it was the strongest one.

One motivation for these matching experiments was to find out whether judgments of the subjective pitch height of OA tones could be used to infer a SHPC. In that respect, both experiments were unsuccessful. Experiment 2A yielded individual differences in response patterns, but few participants showed sufficiently large differences in subjective pitch height among OA tones, and the individual differences were unrelated to those observed in Experiment 1A. Experiment 2B, of course, failed completely in this regard because all participants showed similarly large context effects and no other systematic differences among OA tones. It seems that matching tasks are either not sensitive enough or are in principle unsuited for the assessment of SHPCs. Perhaps SHPCs are indeed an emergent property of pitch-class-based judgments of OA tritone pairs and not a consequence of differences in subjective pitch height among single OA tones. Before concluding this, however, we made another attempt to assess SHPCs by juxtaposing UA and OA tones in a different way.

Experiment 3: judging "mixed" tritone pairs

In Experiment 3, instead of asking participants to match UA and OA tones of the same pitch class, we paired UA and OA tones whose pitch classes were separated by a tritone—a "mixed pairs" version of the tritone paradox paradigm. We thought that judging the relative pitch height of UA and OA tones of different pitch classes might be easier than direct comparisons of UA and OA tones of the same pitch class and might yield more consistent information about the dominant pitches participants perceive in the OA tones. If OA tones (ordered here by ascending pitch class for the sake of argument but randomly ordered in the actual experiment) are paired with increasingly higher UA tones (e.g., C-F#3, C#-G3, D-G#3,…, C-F#4, C#-G4,…), then at some point there should be a more or less abrupt transition from "OA > UA" (OA tone higher than UA tone) to "OA < UA" (OA tone lower than UA tone) judgments. This transition should occur about 3 st below the SHPC, keeping in mind that the OA pitch class continuum is circular whereas the UA pitch continuum is linear. (Effectively, in pairing OA with UA tones we are rolling the OA pitch

[9] It could also be argued that we did not give participants an opportunity to report high-frequency matches because the fundamental frequency range of our comparison tones extended only to about 1,000 Hz. However, the fact that no UA tone with a fundamental frequency between 500 and 1,000 Hz was ever chosen as a match for an OA tone makes it seem unlikely that even higher tones would have been selected if they had been available as choices.

class circle along the UA pitch line.) For example, if the SHPC is G, the mixed pair G-C#3 (or G-C#4, if the dominant pitch of G happens to be an octave higher) should be judged as clearly falling (OA > UA), whereas C#-G3 (or C#-G4) should be judged as clearly rising (OA < UA). The transition then would occur around E3 (or E4) on the UA pitch continuum. That point might also mark the peak of the internal spectral weighting function hypothesized by Terhardt et al. (1986), because according to our interpretation of that theory the subjectively highest OA tone would be the one that has its strongest partial about 3 st above the peak frequency of the weighting function (if the SHPC depended only on internal spectral weighting). If these predictions are correct, the individual SHPCs estimated by the transition points should agree with those found for the same participants in Experiment 1A.

We also investigated the potential influence of UA pitch range and OA spectral envelope on the hypothesized transition point. If the perception of the dominant pitch of OA tones is based on a stable internal weighting function that reflects past auditory experience (e.g., with speech; Deutsch, 1991; Terhardt, 1991), it should not matter whether the tones are being compared more often to high than to low UA tones or the reverse; the transition point on the UA pitch continuum should stay in the same place. However, if perception of the dominant pitch of OA tones is context sensitive (as Experiment 2B indicated, although these results were not yet known when Experiment 3 was conducted), the transition point might shift with the range of comparison tones. Similarly, if the dominant pitch is independent of the spectral envelope of OA tones, at least for spectral envelopes whose peaks differ by only 6 st, then the transition point should be the same for both envelopes. By contrast, if envelope has a strong effect on the SHPC, as in Repp's (1994, 1997) studies, the transition point should be 6 st higher for the tones having the higher envelope.

Finally, we also varied the order of the UA and OA tones within a tritone pair. We thought it possible that UA tones would affect perception of OA tones more when they precede them than when they follow them. If the UA tone comes first, it can influence perception of the OA tone at every stage of the process. If the UA tone comes second, it can affect perception of the OA tone only retroactively, after a dominant pitch percept has already been formed for the OA tone and stored in memory.

Methods

Participants

The participants were the same as in Experiment 1A. Several months elapsed between the experiments, during which the participants were occupied with other experiments not involving OA tones.

Materials

Two sets of OA tones were used whose spectral envelopes were centered on C4 and on F#4, respectively, as in Experiments 1B and 2B. The UA tones here comprised 30 different tones ranging from E2 to A4 (MIDI pitches 40–69; 82–440 Hz). They were divided into two overlapping sets of 24 tones each, one ranging from E2 to D#4 ("low range"), and the other one ranging from A#3 to A4 ("high range"), representing an upward frequency shift of 6 st. Each UA tone in each pitch range was paired with an OA tone whose pitch class differed by 6 st. (Thus, each OA tone was paired with two UA tones, an octave apart, in each pitch range condition.) The factorial combination of two sets of UA tones (low or high range), two sets of OA tones (C4 or F#4 envelope), and two orders of the tones within a pair (UA–OA or OA–UA) resulted in 8 sets of 24 tritone pairs each.

Procedure

Each participant completed 3 blocks of 24 randomly ordered trials for each of the eight conditions before going onto the next condition (24 blocks total). The order of conditions was approximately counterbalanced across the 11 participants according to a 2 × 2 × 2 Latin square, with three orders occurring twice. Range of UA tones varied most slowly (first vs. second half of the session), and order of UA and OA tones varied most rapidly (alternating from one condition to the next). Participants sat in front of a computer monitor that displayed a "start block" button, three response buttons, and a "next trial" button. Each trial started with an onset delay of 1 s after the "start block" or "next trial" button was clicked. Each tone sounded for 500 ms, with inter-onset interval of 1 s between the two tones. Participants selected one of three answer choices, "rising," "falling," or "not sure," before clicking the "next trial" button. After each block of 24 trials, there was a brief pause during which the data were saved and the next block was selected.

Results

Participants had little difficulty judging the relative pitch height of UA and OA tones in mixed tritone pairs. The total percentage of "not sure" responses was 9.6%. As in Experiment 1, we counted each of these responses as half a "rising" or "falling" response. To be able to compare the results for the two order conditions, we analyzed "OA < UA" responses ("rising" for OA–UA and "falling" for UA–OA).

With regard to the effect of the pitch range of the UA tones, we considered several possible ways of analyzing the data. One was to focus on the mixed tritone pairs that were shared between the two UA ranges and to ignore responses to pairs that occurred in only one of the ranges. The results of that analysis were very similar to those obtained from an alternative analysis that we will describe instead. In that analysis, we considered the responses to all tritone pairs and estimated the transition point (defined as the point at which cumulative "OA < UA" responses as a function of increasing UA pitch reach 50%) for each of the eight conditions and each participant as follows: first we computed the proportion of "OA < UA" responses for each tritone pair across the three blocks of trials; then we summed these proportions across the 12 tritone pairs and subtracted the sum from the highest MIDI pitch number in the range of UA tones; finally, we added 0.5 to the result because, if exactly half of all responses were "OA < UA," the transition point should be halfway between the 12th and 13th MIDI pitch in the UA range of 24 pitches. This method yields a transition point estimate regardless of how the responses are distributed or whether they ever reach 50%.

The mean transition point estimates for the eight conditions are shown in Fig. 8. They fall between MIDI pitch numbers 55 and 62 (G3-D4, 196–294 Hz), consistent with Experiment 2. A 2 × 2 × 2 repeated measures ANOVA revealed three significant effects. First, there was a strong main effect of UA pitch range, $F(1, 10) = 91.52$, $P < 0.001$, due to higher transition points in the high-range condition than in the low-range condition; the mean difference was 3.7 st. The difference indicates that OA tones were perceived as relatively higher when they occurred in the context of a higher range of UA pitches (i.e., an assimilative context effect, as in Experiment 2B). The second significant effect was a main effect of envelope, $F(1, 10) = 12.94$, $P = 0.005$: OA tones with the F#4 envelope were heard as relatively higher than those with the C4 envelope; however, the effect was small, a mean difference of 1.3 st, again similar to Experiment 2B. Finally, there was an interaction of order and envelope that just barely reached significance, $F(1, 10) = 5.02$, $P = 0.049$: the effect of envelope was slightly larger when the OA tones occurred second in the tritone pairs than when they occurred first. Figure 8 also suggests that OA tones tended to be heard as higher when they occurred first than when they occurred second in a tritone pair (a mean difference of 1.6 st), but the main effect of order did not reach significance, $F(1, 10) = 3.21$, $P = 0.103$, due to large individual differences.

A third way of analyzing the data would have been to fit sigmoid curves to the individual cumulative response functions in each condition and estimate the individual 50% crossovers. However, for some participants the response percentages stayed below 50% in the low-range condition.

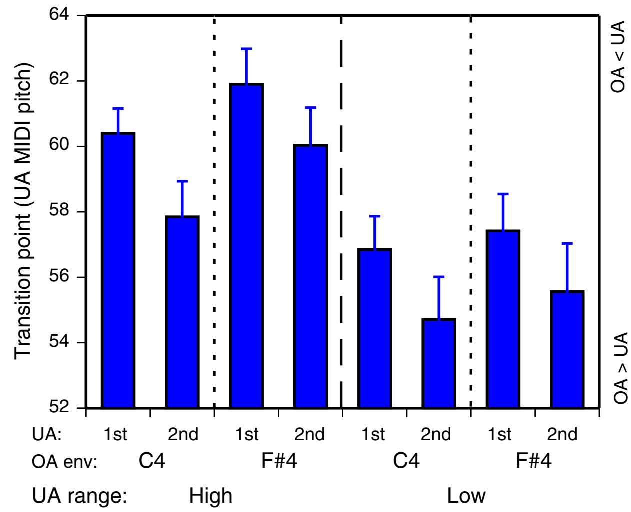

Fig. 8 Experiment 3: mean transition points between "OA > UA" and "OA < UA" responses on the UA pitch continuum in eight conditions, with standard *error bars*

Also, the individual response functions were rather noisy due to the small amount of data in each condition, and sometimes they were non-monotonic. Nevertheless, they revealed some interesting individual differences. In Fig. 9 we have plotted two response functions for each individual participant. They are for the two range conditions, with the responses pooled across envelope and order conditions. Instead of curve fitting, the functions were smoothed with a 3-point window. Their literal 50% crossovers are indicated, with the closest UA pitch number shown next to each (see also Table 1, last two columns).

First, it can be seen that all participants showed UA range effects, though of varying magnitude. Curiously, the two participants showing the largest (assimilative) range effects were the ones who had shown *contrastive* context effects in Experiment 1A (Ce, Pi3). Other participants' range effects show no obvious relation to priming effects in Experiment 1A.

Next, we note the remarkably similar results of the four participants in the lower right-hand part of Fig. 9 (Cl1, Cl2, Ha, and Cl3). These same individuals had shown very similar results in Experiment 1A as well. Their present results indicate that they perceived the OA tones as rather high. (There had been no indication of this in Experiment 2A, however.) Their 50% crossovers were outside the low UA range, near MIDI pitches 64 and 65 (E4 and F4, 330–349 Hz). This agrees quite well with these participants' SHPCs in Experiment 1A, which were G or G# (see Fig. 3; Table 1), 2–3 st above the crossover, as predicted. The remaining six participants generally had monotonic response functions with 50% crossovers ranging from as low as 51 (D#3, 156 Hz) to as high as 64 (E4, 330 Hz). Some of the crossovers agree roughly with the Experiment

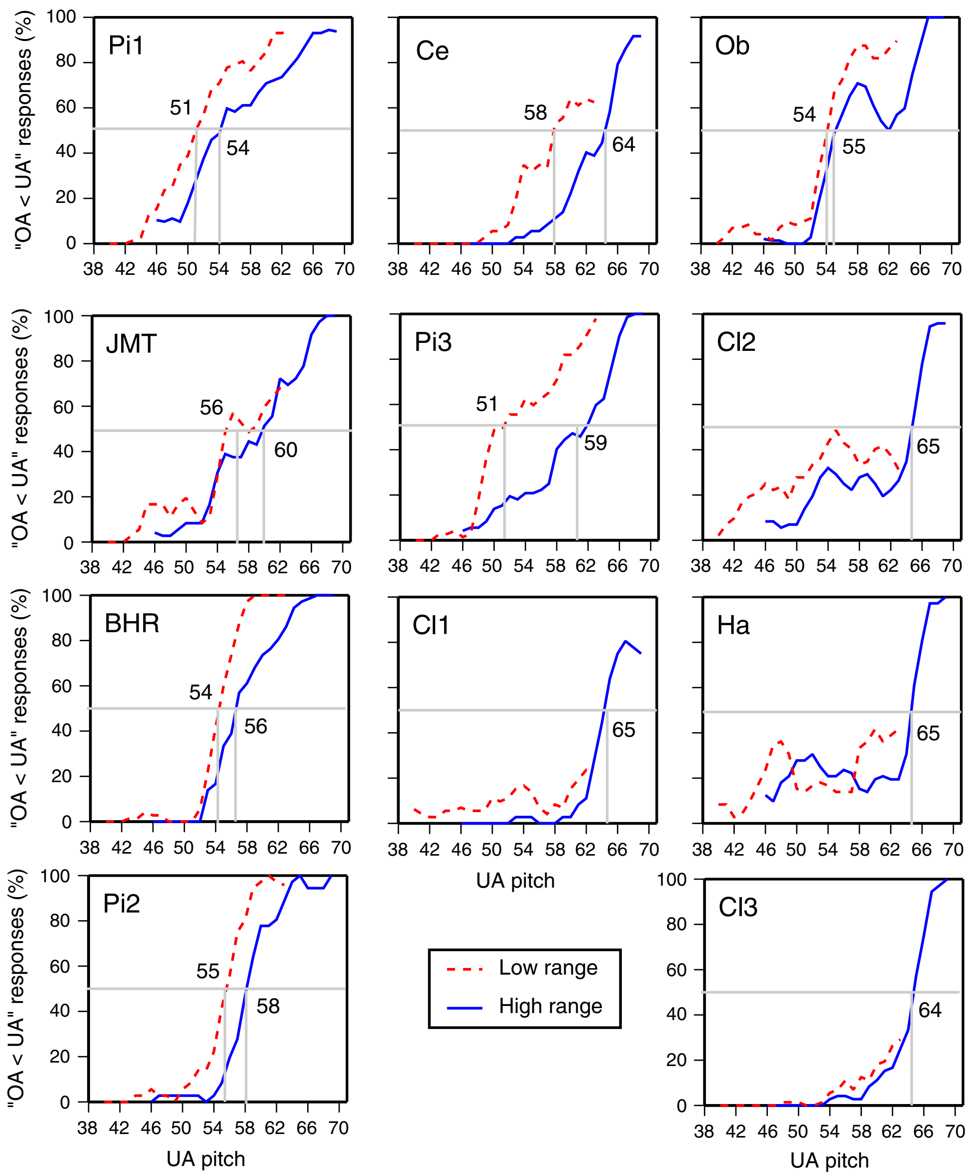

Fig. 9 Experiment 3: individual percentages of "OA < UA" responses as a function of increasing UA pitch (labels and arrangement as in Figs. 3, 5). Individual response functions have been smoothed and averaged across envelope and order conditions. *Gray lines* indicate 50% crossovers of functions; numbers are the corresponding UA pitches (rounded to the nearest semitone)

1A data, but most do not (see Table 1). In general, the presence of range effects (as well as of envelope and order effects) in the present data makes it difficult to establish clear relationships with the data of Experiment 1A.

Discussion

In this experiment we used a novel "mixed tritone pairs" paradigm to assess perception of the dominant pitch of OA tones. Participants clearly were able to judge the relative pitch height of OA and UA tones when their pitch classes were a tritone apart, which validates the concept of a dominant virtual pitch for OA tones.

We examined the effects of three independent variables: the pitch range of the UA tones, the spectral envelope of the OA tones, and the order of the two types of tone within the tritone pairs. Pitch range had the clearest effect: participants perceived the same OA tones as higher when they occurred in the broader experimental context (half a session) of a high range of UA tones than when they occurred in the context of a low range of UA tones. However, the difference between the high and low UA ranges was 6 st, whereas the average effect on OA tone perception was only 3.7 st. Thus, UA tone range did not completely determine the perceived pitch height of OA tones, consistent with the results of Experiment 2B. It should be noted that the range effect could have been due to the timbre (spectral content) as well as, or even instead of, the pitch (fundamental frequency) of the UA tones because the frequency content of unfiltered harmonic complex tones necessarily gets higher as the fundamental frequency increases. For example, the higher spectral center of gravity of high-range UA tones may have raised participants' internal spectral weighting function for OA tones.

The spectral envelope of the OA tones also had a reliable effect: OA tones with an envelope centered on F#4 were perceived as higher than OA tones with an envelope centered on C4. The effect was only 1.3 st, however, whereas the envelope was shifted by 6 st. Clearly, it is not the case that the dominant pitch of OA tones is determined by the spectral envelope, and in that respect the present results are consistent with those of Terhardt et al. (1986) as well as with various studies of the tritone paradox that have found little or no effect of different spectral envelopes on judgments of OA tritone pairs (Dawe et al., 1998; Deutsch, 1987, 1991; Deutsch et al., 1987; Giangrande, 1998).

The order of the OA and UA tones within a pair did not have a reliable effect, due to large individual differences. However, spectral envelope had a greater effect when the OA tone occurred second than when it occurred first in a pair. This is difficult to explain because the envelope is a property of the OA tone alone, and it is unclear how a preceding UA tone might have increased the envelope effect. Perhaps having to remember the dominant pitch of the OA tone when it occurred first enabled participants to achieve a better separation of pitch and timbre.

General discussion

Research on the tritone paradox has given rise to the concept of a subjectively highest pitch class (SHPC) among the 12 pitch classes represented by a set of OA tones with the same spectral envelope. The concept is based on the finding that most participants judge some OA tones to be higher than others from the same envelope set when they are presented as tritone pairs. The SHPC is an abstraction; it is the weighted center of the six adjacent pitch classes that tend to be judged as higher than the other six. The SHPC differs among individuals but is generally considered stable for each individual and almost independent of the spectral envelope of the OA tones (Deutsch, 1987).

If one OA tone is judged as higher than another OA tone whose pitch class differs by 6 st, this seems to imply that the dominant pitch of the first tone is higher than that of the second tone, at least at the time the judgment is made. According to Terhardt (1991; Terhardt et al., 1986), the relative salience of an OA tone's candidate virtual pitches is determined by a perceptual weighting scheme that favors frequencies near 300 Hz. Individuals may differ in the precise location of the peak of the weighting function, but for each individual the location of the peak, which determines the SHPC, is assumed to be determined by past auditory experience and therefore presumably stable.

In the present study, we were concerned mainly with these stability assumptions. Both individual OA tones and tritone pairs of OA tones are perceptually multistable: individual tones, in that they can be perceived as having their dominant pitch ("fundamental frequency") in two or three different octaves, and tritone pairs, in that they can be perceived as rising or falling in pitch, or even as rising and falling at the same time. In Experiment 1, we attempted to bias relative pitch judgments of pairs of OA tones by preceding them with a pair of UA tones that clearly instantiated a rising or falling tritone interval. About half of the participants proved to be immune to such priming. Of the other half, some showed positive priming, others showed negative priming. Thus, some individuals' perception of relative pitch height in OA tritone pairs is not stable and can be influenced by UA context. The SHPC, however, changed little in all cases. This suggests that contextual influences, when they did occur, indeed took place at the level of relative pitch judgment, not at the level of absolute (dominant) pitch perception because changes at that level would entail changes in the SHPC.

In Experiment 2A we asked participants to match individual OA tones to UA tones, in order to find out what the dominant pitch of the OA tones might be. The general response distribution showed a peak around 260 Hz, which is roughly consistent with the findings of Terhardt et al. (1986). Our response distribution was narrower than theirs, however, which we attribute to our use of complex harmonic tones as UA comparison stimuli and to the narrower spectral envelope of our OA tones. The OA tones judged to be highest in pitch were close to the mean SHPC in Experiment 1. However, there was not much differentiation among OA tones and little agreement at the individual level between the results of Experiments 1A and 2A. Thus, the matching task does not seem well suited to assessing SHPCs.

This impression was reinforced by Experiments 2B and 3, both of which demonstrated strong contextual influences of UA tones on the judged dominant pitch of OA tones. The higher the pitch of UA comparison tones, the higher the OA tones were judged to be. This finding indicates that the hypothetical spectral weighting function that governs the perceived dominant pitch of OA tones is flexible and context dependent. Changes in the weighting function imply a change in SHPC. Thus, to assess SHPCs, OA–UA matching or comparison paradigms are not suitable alternatives to the standard tritone paradox paradigm in which only OA tones occur. Whether the SHPC in the standard paradigm depends on perceived pitch height at all remains uncertain. It is possible that the SHPC is an emergent property of a self-organizing perceptual process within a closed set of OA tones (cf. Giangrande et al., 2002) and has nothing to do with the judgment of single OA tones in relation to UA tones. Although the experiential determinants of the SHPC hypothesized by Deutsch (1991) are essentially the ones that Terhardt (1991) hypothesized to underlie the internal spectral weighting function (i.e., exposure to speech), the apparent stability of the SHPC (Experiment 1 and previous tritone paradox research) contrasts with the apparent malleability of the internal weighting function (Experiments 2B and 3). This malleability may come about through automatic inclusion of all tones heard, whether UA or OA, in a process of perceptual calibration.

Experiments 2B and 3 also investigated the role of the spectral envelope of OA tones by contrasting tones with envelopes centered on pitches 6 st apart. In both experiments, envelope had a significant but small effect on judged pitch height relative to UA tones. Thus, tones with a spectral content of higher frequencies were perceived as slightly higher in pitch, which is consistent with interactions between timbre and pitch perception found in other paradigms, though mainly in non-musicians (Krumhansl & Iversen 1992; Pitt, 1994; Preisler, 1993; Seither-Preisler et al., 2007). The relatively small size of the envelope effect is consistent with findings of similarly small or nonexistent envelope effects in the tritone paradox by Deutsch (1987) and others, and in a pure-tone matching task by Terhardt et al. (1986). It appears that the judged pitch height of OA tones indeed depends more on (context dependent) internal spectral weighting than on the physical structure of the tones, although it remains to be seen whether that is still true when envelope differences much larger than 6 st are introduced.

This study was not intended as an investigation of the experiential determinants of the individual SHPC, which Deutsch (1991) famously hypothesized to be linguistic in nature—a hypothesis much in need of further supportive data. Our data contribute little to this issue save for a suggestion that experience with musical instruments may matter, too: four players of wind instruments and a harpist showed strikingly similar results, in both Experiments 1A and 3. Perhaps the SHPC and the internal spectral weighting function are reflections of the total auditory history of individuals, which has shaped their auditory systems in the course of many years. This hypothesis gains plausibility from recent findings of neural plasticity at even very early levels of auditory processing (e.g., Kraus & Banai, 2007; Luo et al., 2008).

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