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ACOUSTIC SIGNAL PROCESSING AND COMPUTER SIMULATION

Virtual Pitch Extraction from Harmonic Structures by Absolute-Pitch Musicians[1]

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Abstract—The ability of absolute-pitch (AP) musicians to identify or produce virtual pitch from harmonic structures without feedback or an external acoustic referent was examined in three experiments. Stimuli consisted of pure tones, missing-fundamental harmonic complexes, or piano notes highpass filtered to remove their fundamental frequency and lower harmonics. Results of Experiment I showed that relative to control (non-AP) musicians, AP subjects easily (>90%) identified pitch of harmonic complexes in a 12-alternative forced-choice task. Increasing harmonic order (i.e., lowest harmonic number in the complex), however, resulted in a monotonic decline in performance. Results suggest that AP musicians use two pitch cues from harmonic structures: 1) spectral spacing between harmonic components, and 2) octave-related cues to note identification in individually resolved harmonics. Results of Experiment II showed that highpass filtered piano notes are identified by AP subjects at better than 75% accuracy even when the note's energy is confined to the 4th and higher harmonics. Identification of highpass piano notes also appears to be better than that expected from pure or complex tones, possibly due to contributions from familiar timbre cues to note identity. Results of Experiment III showed that AP subjects can adjust the spectral spacing between harmonics of a missing-fundamental complex to accurately match the expected spacing from a target musical note. Implications of these findings for mechanisms of AP encoding are discussed.

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INTRODUCTION

Virtual pitch, also known as periodicity or residue pitch refers to the perception of a pitch associated with the fundamental frequency of a missing-fundamental complex presumed to exclusively involve synthesis through higher-order computational processes [1–10, for reviews see 11, 12]. The salience of virtual pitch depends on several factors including the number of harmonics, harmonic order, spectral region and relative phase across harmonic components [13–15]. As such, virtual pitch has often been used to test competing models of pitch encoding including temporal or autocorrelation models [9, 16], power spectrum models (i.e., peripheral place coding; [17, 18]), and template-matching or pattern-recognition models [1, 7, 9, 10, 13].

Absolute pitch (AP) refers to the rare ability of some musicians in identifying the pitch of a musical note from long-term memory without an acoustic referent ([19–24]; for reviews see [25, 26]). Theories of AP encoding, supported by psychophysical and neuroimaging evidence, have proposed an intrinsic association between stored pitch representations and higher-order linguistic processes in facilitating the retrieval and labeling of pitch from memory [26–28]. No prior study has investigated the ability of AP musicians to process virtual pitch. This is an important question because involvement of a centrally mediated cognitive mechanism in AP processing which invokes a hypothesized conditional association between pitch and linguistic representations may affect identification of a *centrally* generated pitch (i.e., virtual pitch) differently than that of pitch with a peripheral origin[2] (e.g., pure tones, narrowband noise, fundamental frequency of complex sounds).

We address here the question of whether virtual pitch can be identified or produced by AP musicians as easily as pitch extracted from low-frequency cues at the fundamental frequency. Specifically, we examine

[1] The text was submitted by the authors in English.

[2] By centrally synthesized pitch we mean a pitch whose final neural computations are carried out beyond the initial stages of auditory processing. The virtual pitch of a harmonic complex must be calculated at cortical stages that combine information (either temporal or spectral) from tonotopically organized earlier stages in the auditory tract. In contrast, the pitch of pure tones or narrowband noise does not require synthesis across separate frequency bands and may be represented as having a tonotopic peripheral origin.

in three experiments the ability of AP and control musicians to identify the pitch of musical notes composed either of missing-fundamental harmonic complex tones, or piano notes highpass filtered to eliminate their fundamental and lower harmonics. In addition, we examine AP ability as virtual-pitch salience is systematically degraded by increasing the harmonic order (i.e., the lowest harmonic number in the stimulus) and decreasing the number of harmonics to as few as two. We also address the question of whether error patterns associated with virtual pitch *production* are significantly different than those for identification, given the recent evidence that perception and production of absolute pitch may utilize fundamentally different access mechanisms to pitch memory [28–30].

GENERAL METHODS

Subjects. Ten trained musicians (5 AP and 5 non-AP) participated in the study. Seven of the subjects were undergraduate piano performance or composition/drama majors in the Music Department at the University of California, Irvine. The other 3 were non-music majors but were highly trained pianists with over 10 years of experience. AP and non-AP groups had average ages of 22 (range 19–27) and 19.2 (range 18–21) years, and had begun formal music training at 5 (range 4–6) and 5.8 (range 4–8) years of age, respectively. AP and non-AP subjects had an average of 14 and 13.2 years experience playing their primary instrument. While subjects typically were trained in more than one instrument, piano was the primary instrument of all 10 subjects. Subjects were recruited either through flyers posted around the Music Department or verbally at music performance classes. Subjects gave their written informed-consent to participate. All protocol were approved by the UC Irvine Institutional Review Board.

Screening for AP. Subjects were screened for AP ability using protocol similar to those described by Baharloo et al. [23]. Stimuli consisted of 50 pure tones and 50 piano notes presented in two blocks of 50 trials each. A predetermined criterion of 90% accuracy for identifying piano notes and 80% for pure tones was used to qualify a subject as AP [23, 31, 32]. Pure tones were 1s in duration with 100ms rise-decay ramps. Piano notes were digitally recorded from a 9-foot Steinway grand piano at UCI's Music Department. Notes were recorded at a sampling rate of 44.1 kHz using a 0.5-inch microphone (Brüel & Kjær Model 4189), a conditioning amplifier (Nexus, Brüel & Kjær), and a 16-bit A-to-D converter (Creative Sound Blaster Audigy 2ZS). Stimuli were presented diotically at a sampling rate of 44.1 kHz through Bose headphones (model QCZ, TriPort) in a double-walled steel acoustically isolated chamber (Industrial Acoustics Company). On each trial a musical note was randomly selected from C2 to B6 (65.4 to 1975.5 Hz; A4 = 440.0 Hz) with the constraint that two successive notes were at least 2 octaves + 1 semitone apart. A 600ms burst of white Gaussian noise was presented 600ms after termination of each stimulus, followed by 1200ms of silence during which subjects responded. The noise was introduced to reduce iconic (sensory) trace memory cues. Subjects were asked to identify each note by selecting 1 of 12 note labels on GUI (graphical user interface) push-buttons. Subjects were not provided reference stimuli, practice trials, or feedback at any time during screening or experiments.

Participants received 1 point for correct identification and 0.5 point for identification within a semitone (e.g., C vs. C#; [see ref. 23]). To qualify as AP, we required a minimum score of 45 points (90%) for piano notes and 40 (80%) for pure tones (maximum = 50 points). Averaged scores across 5 AP subjects were 48.8 ($\sigma = 1.26$) for piano notes and 43.8 ($\sigma = 2.36$) for pure tones. Non-AP subjects had average scores of 17.0 ($\sigma = 5.79$) and 13.2 ($\sigma = 2.93$) for piano and pure tones, respectively (chance performance = 8.3 points). The slightly above-chance performance by non-AP musicians is consistent with previous studies [23, 26, 33]. Restricting scoring to exact identification, AP subjects had an average score of 48.0 ($\sigma = 1.87$) or 96% for piano notes and 40.0 ($\sigma = 4.62$) or 80% for pure tones. Non-AP subjects scored 13.8 ($\sigma = 6.97$) or 27.6% for piano notes and 7.2 ($\sigma = 3.42$) or 14.4% for pure tones (chance performance = 4.1 points or 8.3%).

EXPERIMENT I: IDENTIFICATION OF THE PITCH OF MISSING-FUNDAMENTAL HARMONIC COMPLEXES AS A FUNCTION OF THE NUMBER OF HARMONICS

Stimuli. Stimuli consisted of zero-phase missing-fundamental harmonic complex tones (Eq. (1)) with the fundamental frequency (F_0) selected from the range of C2 to B6 (65.4–1975.5 Hz) equivalent to the range of pure-tone frequencies used in the screening task and similar to the range used in other studies. Specifically, the harmonic complex was of the form:

$$X(t) = \sum_{k=2}^{n+1} \sin(2\pi(kF_0)t)W(kF_0), \tag{1}$$

where W is the frequency-dependent weighting function derived from equal loudness contours (ELC) to match harmonic components for loudness, and n is the highest harmonic number in the complex.

On each trial F_0 was selected randomly with the constraint that on successive trials notes would differ by at least 2 octaves + 1 semitone [23]. Eight different missing-fundamental conditions were examined which differed from each other in their harmonic structure. The eight types of complex tones were composed of: 1) first five harmonics, 2) first 4 harmonics, 3) first 3 harmonics, 4) first 2 harmonics, and 5) the first harmonic alone (these conditions are referred to

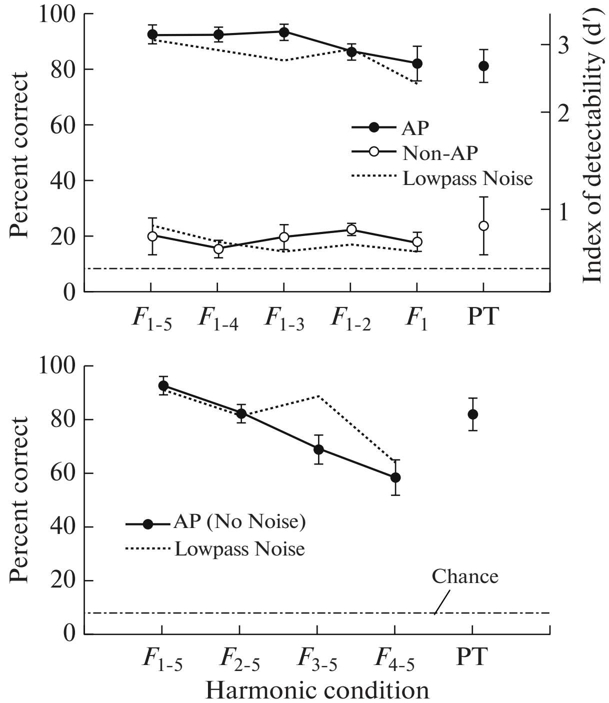

Fig. 1. Pitch identification performance by AP and non-AP subjects. Stimuli were missing-fundamental harmonic complexes. Top panel: PT= pure tone; F_{1-5} = complex tone consisting of first 5 harmonics; F_{1-4} = first 4 harmonics; etc. Bottom panel shows effects of changing harmonic order (lowest harmonic # in the complex): F_{1-5} = complex tone consisting of first 5 harmonics; F_{2-5} = harmonic numbers 2 to 5; etc. Data are averaged from 5 AP musicians. Dashed horizontal lines at bottom of each panel indicate chance performance. Error bars are +/−1 standard deviation.

as F_{1-5}, F_{1-4}, F_{1-3}, F_{1-2}, and F_1, respectively). Conditions 6 to 8 consisted of increasing harmonic order and included: 6) harmonics 2 to 5 (F_{2-5}), 7) harmonics 3 to 5 (F_{3-5}), and 8) harmonics 4 and 5 (F_{4-5}). To examine the potential use of nonlinear intermodulation distortions at the fundamental frequency, we ran a control condition with addition of lowpass filtered noise (60 dB SL) with a cutoff frequency halfway between F_0 and F_1 [14]. All stimuli were 1000 ms in duration with linear rise/decay ramps of 100 ms.

Procedure. The experiment was run in a block design with each of 8 conditions fixed within a run. Each run consisted of 50 trials in which a randomly selected note (harmonic complex) was presented on each trial, followed by a 600ms white Gaussian noise-burst, followed by 1200 ms of silence. During the 1800 ms ISI, participants responded by selecting from 12 musical-note labels (listed in both Western and Solfeggio notations, i.e., *La#* (*A#*)) arranged in 2 rows of 6 GUI push-buttons on the monitor. Each trial was initiated by pressing a 'Start' button on the screen. Subjects were required to respond immediately after presentation of each note. Neither reference tones nor feedback were provided at any point during the experiment. Participants completed the various experimental conditions and their corresponding control conditions (low-pass noise) in a randomized order. Data were scored in terms of identification accuracy following the protocol described earlier.

Results. Percent correct performances for the first five conditions are shown in the top panel of Fig. 1 for both AP (filled symbols) and non-AP subjects (open symbols).[3] Dashed lines next to each set of symbols represent performance in the control lowpass-noise condition. Chance performance is shown by the dashed horizontal line at the bottom of each panel. Performance for pure-tone stimuli from the screening task are also shown for comparison (PT). Error bars are +/−1 standard deviation. Mean percent correct across all harmonic conditions was 89.4 ($\sigma = 4.8$) for AP subjects and 19 (3.0) for non-AP subjects. For comparison, on the right ordinate of the top panel, we show d' values (index of detectability) derived from equations provided by Elliott [34] for a 12-alternative forced-choice task. Clearly, AP subjects significantly outperformed non-AP subjects, although there is no significant effect of harmonic condition. AP subjects also generally performed slightly better in most of the harmonic conditions than the pure-tone condition. The addition of lowpass filtered noise had no significant effect on performance.

Multiple cues from harmonic structures. Restricting pitch cues to a note's harmonic structure excludes energy at the fundamental frequency of that note. However, this harmonic structure contains both a pitch cue derived from the relationship among harmonics, as well as a pitch cue derived from individual-components. The first and third harmonics of a target note have an octave relationship with the target frequency. Although these components are heard in the presence of other components with their own resolved pitches, octave-related cues derived from resolved harmonics do contributed to note identification, hence the slightly better performance in the harmonic conditions (which contain both virtual and octave-related cues) relative to the pure-tone condition.

Effects of harmonic order. Bottom panel of Fig. 1 shows the effects of increasing harmonic order from 1 to 4 (conditions 1, 6–8). Data were collected only from AP subjects since non-AP subjects could not perform the task even when all five harmonics were present. AP subjects clearly perform considerably above chance in all harmonic-order conditions, though there is a clear decline in performance when the stimulus contains only the 4th and 5th harmonics. Nonetheless, even in this condition, subjects score above 60%. The decline in performance with increasing harmonic order may as discussed in the previous

[3] Scores shown are based on exact identification of a musical note, with no additional points given for correct identification to within a semitone as described for the screening task.

section be partially accounted for by the dual-pitch cue in harmonic structures. Note, for example, that the stimulus containing only the 4th and 5th harmonics excludes octave-related cues.

Error patterns. Figure 2 shows error patterns associated with all 8 stimulus conditions (no noise). Top and middle panels show data from conditions 1 to 5 for AP and non-AP subjects respectively, and bottom panel shows effects of increasing harmonic order (conditions 1, 6, 7 and 8 for AP subjects). When AP subjects do make errors, these are generally as small as a semitone. The error distribution for non-AP subjects has a high variance and is monotonic decreasing with distance from target note.

EXPERIMENT II: IDENTIFICATION OF THE PITCH OF HIGHPASS FILTERED PIANO NOTES

Previous studies have reported that AP subjects often perform better when identifying the pitch of musical instruments compared to pure tones, presumably because of the rich harmonic structures of the latter stimuli which provides both octave and timbre cues to musical-note identity. In Experiment II, we measured AP identification of piano notes highpass filtered to remove their fundamental frequency and lower harmonics.

Stimuli & Procedures. Stimuli were filtered versions of the digitally recorded piano notes used in the screening procedure. Four stimulus conditions were examined defined by how the piano notes were filtered. The four conditions were: 1) removing the fundamental frequency F_0, 2) removing F_0 and the first harmonic, 3) removing F_0, F_1, and F_2, and 4) removing F_0, F_1, F_2, and F_3. These conditions are referred to as F_{1-n}, F_{2-n}, F_{3-n}, and F_{4-n} respectively. Stimuli were digitally filtered in Matlab by Fast Fourier Transforming (FFT) each waveform, removing the fundamental and/or lower harmonics, and inverse transforming to the time domain. To preserve the original timbre of the remaining harmonics, no ELC weighting was applied to the stimuli. In a control condition, lowpass noise with a cutoff frequency halfway between the fundamental and the lowest harmonic (e.g., F_2 in condition 2) was added to each filtered piano note. Stimuli were normalized to equal r.m.s. by dividing each waveform by its standard deviation. This was necessary since highpass filtering piano note resulted in low intensities nearing the audibility threshold. The same 10 subjects participated in Experiment II, and all procedures were identical to those used in Experiment I.

Results. Figure 3 shows results of this experiment. AP subjects performed at 89.6, 83.6, 81.6, and 73.6% accuracy in the four stimulus conditions respectively (F_{1-n}, F_{2-n}, F_{3-n}, and F_{4-n}). Non-AP subjects performed at 20.0, 16.0, 11.5, and 16.0% in the 4 conditions. As was the case for Experiment I, addition of

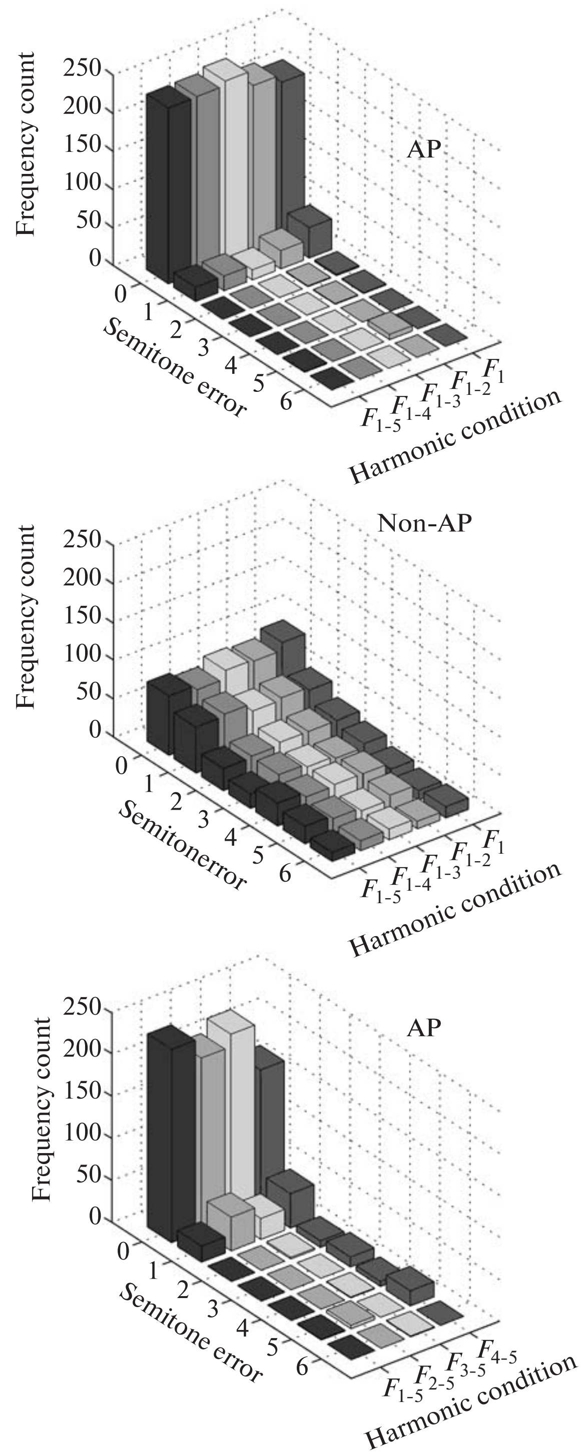

Fig. 2. Distribution of errors in identifying the musical pitch of missing-fundamental complex tones. Deviations from the target note are shown in semitone units (0-semitone represents exact identification, i.e., no error). Each panel shows data combined from 5 subjects. Top and middle panels show data from conditions 1 to 5 from AP and non-AP subjects respectively (i.e., data from top panel of Fig. 1). Bottom panel shows data from conditions 1, and 5 to 8 from AP subjects (i.e., data from bottom panel of Fig. 1).

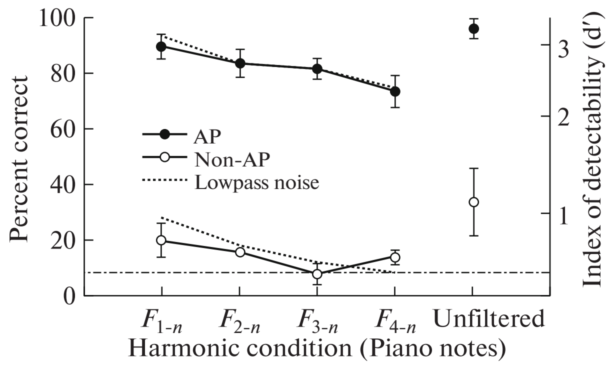

Fig. 3. Identification of the pitch of highpass filtered piano notes by AP and non-AP subjects. Abscissa shows stimulus conditions with F_{1-n} corresponding to piano notes whose fundamental frequency (F_0) has been filtered out, F_{2-n} corresponding to a piano note with the fundamental and first harmonic filtered out, etc. Data are averaged from 5 AP and 5 non-AP musicians. Dashed horizontal line indicates chance performance. Error bars are +/−1 standard deviation.

lowpass masking noise did not significantly affect performance (dashed lines). Distribution of error patterns from this experiment are shown in Fig. 4.

Performance of AP subjects slightly declines as the lower harmonics are filtered out. Nonetheless, even in the poorest condition ($F_{4\text{-}n}$) they perform significantly above chance (>70%; chance = 8.3%). This level of performance is better than that for the 2-tone harmonic condition (F_{4-5}) from experiment I, possibly because of both the presence of higher harmonics (>5$^{\text{th}}$) in piano notes as well as timbre cues. Fourier analysis of the recorded piano notes showed that for notes in the lower and middle octaves, partials above the 5$^{\text{th}}$ harmonic contain considerable energy, which at times is substantially greater than that of the note's fundamental frequency. Conversely, piano notes from the highest octaves had very weak harmonic structures, with most of the stimulus energy confined to F_0.

EXPERIMENT III: PITCH PRODUCTION BY ADJUSTING THE SPECTRAL SPACING OF HARMONIC COMPONENTS

Stimuli. Stimuli consisted of either pure tones or missing-fundamental 5-harmonic complex tones. Subjects adjusted an unlabeled GUI slider on the monitor to change the stimulus frequency (i.e., the pure-tone frequency or the missing F_0 of a harmonic complex). Changing the frequency of the missing F_0 changes both the spectral spacing and absolute frequency of all components. The range of frequencies that could be selected using the slider depended on the target note frequency which itself was randomly chosen on each trial. This range was kept constant at 3/4 of an octave, but randomly positioned on each trial with respect to the target note frequency. For example, if the target note was 440 Hz (A), the slider could be adjusted in a 3/4 octave range around that frequency, with the 440 Hz point positioned at any location along the slider scale (left edge, right edge, or any point in between). We chose a 3/4 octave range, instead of a full octave, to avoid edge-effects which may increase false-alarm responses. The octave from which a target note

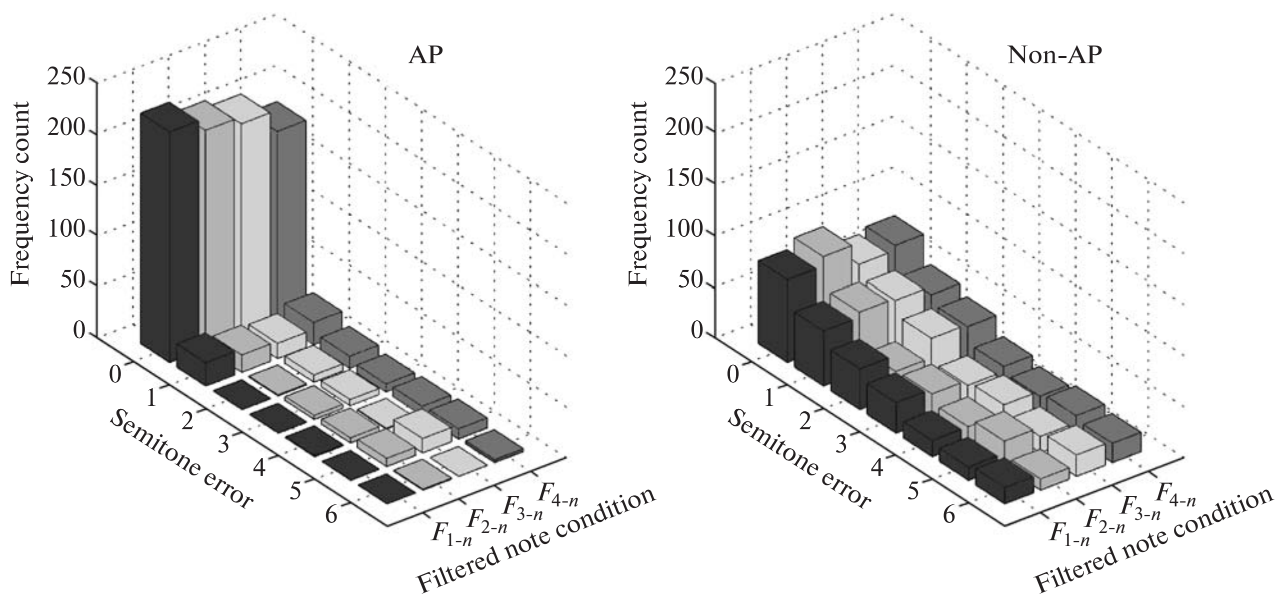

Fig. 4. Error distributions for filtered piano note stimuli. Data are combined from 5 AP (left panel) and 5 non-AP subjects (right panel). Correct pitch identification corresponds to a semitone error of zero.

was chosen was randomly selected from the 2nd to the 6th octaves for the pure-tone stimuli, and due to system limitations, from the 2nd to the 5th octaves for the harmonic complexes. Stimuli were 1000 ms in duration with 100 ms rise-decay ramps.

Procedure. The same 10 subjects participated in Experiment III. At the beginning of each trial, one of the 12 notes was randomly selected without replacement and displayed as text on the screen (i.e., Do(C), Do#(C#), Re, ..., Si(B)). Subjects then immediately adjusted the GUI slider to find the pitch associated with the target note and pressed a GUI push-button after each adjustment to hear the stimulus. Subjects had either 5 or 30 s to make their adjustments on a trial, after which the stimulus could no longer be played for that trial. We selected both a short and a long response period to determine the degree to which pitch-production ability is automatic and effortless, especially for AP subjects. Subjects were allowed to play a given note as many times as they wished during the adjustment period. Typically, they made 4 to 6 adjustments during the 5 s response interval and several more during the 30 s interval, though most subjects (even non-AP subjects) did not use the full 30s as they were satisfied with their final adjustment prior to the end of the interval. When a final adjustment was made on a trial, the subject pressed a separate push-button to record the result. The slider was reset to the middle position at the beginning of each trial.

The experiment was run in a block design in which the stimulus type (pure or complex tone) and adjustment interval (5 or 30s) were fixed within a run. A total of 10 adjustment sessions were run for each of 12 notes, each adjustment interval, and each stimulus type. There were no practice trials allowed and no feedback given at any point during the experiment. Performance accuracy was computed as the average standard deviations in semitone units between the final and target frequency.

Results. Figure 5 shows results of this experiment. Left panel shows results for the missing-fundamental condition, and right panel for pure tones. The ordinate represents average deviation of the slider-adjusted frequencies from standard frequency (i.e., |user-adjusted frequency minus target frequency|). Data are shown for AP and non-AP subjects, as well as for the 5 and 30 s conditions. For the 30s-interval pure-tone condition, AP subjects had an average error of 0.51 semitones, and non-AP subjects showed an average error of 2.87 semitones. For the 5 s-interval pure-tone condition, average errors were 0.55 and 3.07 semitones for AP and non-AP subjects respectively. Results are similar for missing-fundamental complex tones. Average errors for AP subjects were 0.41 and 0.48 semitones for the 30 and 5 s conditions respectively. For the non-AP group, these averages were 1.99 and 3.94 semitones for the 30 and 5 s conditions.

It is clear that non-AP subjects perform significantly better when given additional time, but only in

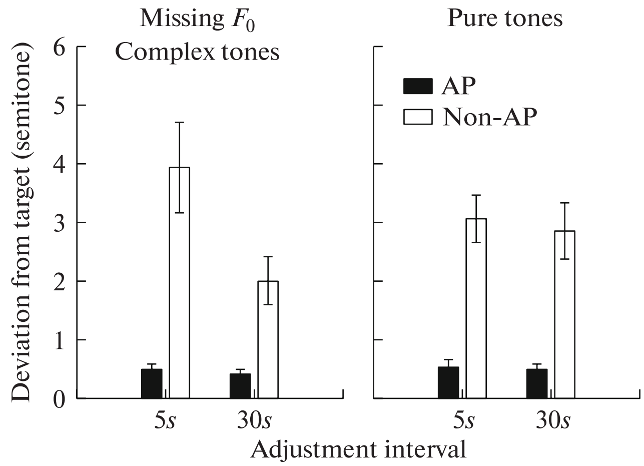

Fig. 5. Average deviations from target-note frequency in a pitch-production task. Subjects were given either 30 s or 5 s to make their final adjustment on a given trial. Left panel shows results for the missing-fundamental harmonic-complex condition and right panel for the pure-tone condition. Error bars are +/−1 standard deviation.

the harmonic condition ($t(4) = 3.917$, $p < .05$). Furthermore, AP subjects produce slightly lower error rates in the harmonic condition than in the pure-tone condition. When non-AP subjects are given only 5 s to produce pitch, they are less accurate in producing virtual pitch than pure-tone pitch, possibly indicating the role of more time-consuming high-order computational or cognitive processes in generation of virtual pitch. This is not evident for AP subjects, given their rapid pitch-coding ability and possibly because of their already low error rates (i.e., a floor effect). Conversely, when given 30 s, these same non-AP subjects are more accurate in producing virtual pitch than pure-tone pitch, suggesting that their poorer performance in the 5 s harmonic-complex condition is not due to a generally less salient pitch cue.

It was unclear a priori whether subjects would display response bias. For instance, non-AP subjects may have produced a small standard deviation of responses but large bias if they consistently adjusted the frequency of the stimulus to a specific but wrong frequency. An analysis of response bias however showed that non-AP subjects made random non-systematic errors resulting in a near-zero bias for both pure-tone and missing-fundamental conditions. The AP group had a near-zero bias, i.e., a constant error CE = −0.11 semitones for pure tones, and CE = −0.18 semitones for harmonic stimuli. The non-AP group also showed no bias, with CE = 0.14 semitones for pure tones, and 0.16 for harmonic tones. Individual-subject analysis confirmed these results (the largest CE for any subject was 0.53 semitones).

DISCUSSION

Two previous studies have examined pitch identification by AP subjects using stimuli that do not require activity at the point on the basilar membrane which would respond maximally to a pure tone of similar pitch. Fujisaki and Kashino [35] reported that iterated rippled noise, a broadband sound consisting of frozen noise iteratively delayed and added to itself, produces a time-based pitch that is accurately identified by AP musicians. IRN stimuli, however, contain weak spectral cues at F_0 and its harmonics. While Fujisaki and Kashino did highpass filter their stimuli above 1kHz, their task involved note identification up to fundamental frequencies of nearly 2 kHz, and thus, spectral energy at F_0 confounded their stimuli on a subset of trials. Ross et al. [36] used a different type of stimulus commonly referred to as Huggins-pitch stimuli which consist of diotic broadband noise with an interaurally phase-shifted narrowband segment. This stimulus produces a weak pitch corresponding to the center frequency of the narrowband noise [37]. Ross et al. reported that AP subjects can accurately adjust the spectral position of the narrowband noise to match the pitch of an acoustic referent presented a few seconds earlier. However, given the presence of a referent sound, it is highly likely that their AP subjects used relative pitch (RP) cues, hence confounding interpretation of their findings. The current study is the first to examine the ability of AP musicians to extract pitch from harmonic structures with a missing fundamental, which either exclusively contain virtual pitch cues (e.g., F_{4-5}) or both virtual and octave-related cues to pitch identity.

Several novel findings emerged from our study. First, AP subjects have no difficulty identifying the centrally synthesized virtual pitch of harmonic structures, though not as easily as that of pure tones or harmonics complexes containing both virtual and octave-related cues (Fig. 2). Second, AP musicians can identify the pitch of harmonic structures containing the first 3 to 5 components more easily than that of pure tones (Fig. 1). Third, time restriction had a selective effect on *producing* the pitch of pure versus missing-fundamental complex tones. AP subjects had no difficulty matching to a target pitch either the pitch of a missing-fundamental complex or the pitch of pure tones. However, non-AP subjects, which perform poorly but above chance in pitch production tasks, showed a more complicated pattern of performance. When adjusting the pitch of pure tones to a target note, time restriction (5 and 30 s) had no effect on performance of non-AP subjects. When adjusting the pitch of complex tones, however, the 5 s condition produced performance poorer than that for the 5 s pure-tone condition. Conversely, these subjects performed better in the 30 s complex-tone condition than the corresponding 30 s pure-tone condition. These findings suggest that the pitch of missing-fundamental complex tones while more salient than that of pure tones, requires longer processing times as expected from a higher-order process. Informal observations of AP and non-AP subjects in the slider-adjustment task showed that AP subjects usually completed their final adjustment on a trial well within 5 seconds, even when they were allowed 30s for adjustment. AP subjects also did not require any practice to become familiarized with slider step adjustments, and appeared to determine their final adjustment rapidly and effortlessly, reporting that it was a fairly easy task [see also refs. 38–40 for temporal and other cognitive constraints on AP processing]. This was in contrast to non-AP individuals who usually experimented with playing sounds along the entire range of frequencies allowed by the slider scale when given sufficient time, suggesting that they may have been attempting to use relative-pitch cues, though such cues could not have been used to determine the target frequency in this task.

Our results with highpass filtered piano sounds are consistent with those for complex tones, and show that overtones of a piano note itself contain sufficient information for pitch identification by AP subjects. One interesting prediction from previous reports is that white-key notes (e.g., C, D) and notes associated with major keys (e.g., C, G) are more easily and rapidly identified by AP subjects than black-key notes (e.g., C#, D#), presumably because piano students commonly start learning white-key pitches first [31, 41, 42], and because white-key notes occur more frequently in musical repertoires in general resulting in a strengthening of memory for such notes. To examine this idea, we analyzed error patterns from our subjects, who all had reported piano as their primary instrument, to determine if response accuracy for pitches associated with black-key notes significantly differed from that for white-key notes. Contrary to previous reports we did not find a significant difference for either AP or non-AP subjects.

In summary, AP subjects can identify and produce pitch derived from harmonics of a musical note as easily as, and in some cases, more accurately than the pitch associated with pure tones. AP subjects are slightly more accurate in identifying the pitch of highpass filtered piano notes than that of complex tones possibly due to contribution of familiar timbre cues, as well as presence of higher harmonic components. Reducing the number of harmonics in a complex from 5 to 1 only slightly affected AP performance but increasing harmonic order from 1 to 4 reduced identification scores by approximately 25%. Non-AP subjects were more accurate in producing pitch from harmonics of a musical note than from pure tones, provided they were given sufficient time (30 s). However, when time was restricted to 5 s, they were less accurate in the harmonic condition, possibly due to involvement of central mechanisms in synthesis of virtual pitch. We observed no effect of time restriction on AP subjects. Finally, the findings from the current study have led us to speculate on a number of potential questions for future research. These include an examination of AP identification of pitch derived from harmonic structures at high frequencies (above 5 kHz) where melodic information is degraded, and an examination of carrier versus envelope cues in absolute-pitch identification.

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