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Research Paper

On the relation between pitch and level

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ABSTRACT

Pitch is the perceptual dimension along which musical notes are ordered from low to high. It is often described as the perceptual correlate of the periodicity of the sound's waveform. Previous reports have shown that pitch can depend slightly on sound level. We wanted to verify that these observations reflect genuine changes in perceived pitch, and were not due to procedural factors or confusion between dimensions of pitch and level. We first conducted a systematic pitch matching task and confirmed that the pitch of low frequency pure tones, but not complex tones, decreases by an amount equivalent to a change in frequency of more than half a semitone when level increases. We then showed that the structure of pitch shifts is anti-symmetric and transitive, as expected for changes in pitch. We also observed shifts in the same direction (although smaller) in an interval matching task. Finally, we observed that musicians are more precise in pitch matching tasks than non-musicians but show the same average shifts with level. These combined experiments confirm that the pitch of low frequency pure tones depends weakly but systematically on level. These observations pose a challenge to current theories of pitch.

1. Introduction

Pitch is the perceptual dimension along which tones are ordered from low to high on a musical scale. For musical tones, the main physical attribute that determines pitch is the repetition rate or fundamental frequency of the sound's waveform (Oxenham, 2012). Accordingly, theories of pitch perception, which can be broadly categorized as emphasizing either temporal cues or cochlear place of activation, have focused on how the auditory system might extract fundamental frequency (de Cheveigne, 2005). Recent psychophysical work has focused on distinguishing between these theories by assessing the perception of relatively complex pitch-evoking sounds, for example dichotic sounds (Bernstein and Oxenham, 2003), transposed tones (Oxenham et al., 2011) or mistuned harmonics (Hartmann and Doty, 1996). In this study, we wanted to address a more basic question: to what extent is the pitch of musical tones the perceptual correlate of fundamental frequency (for complex tones) or frequency (for pure tones)? In other words, is there a one-to-one mapping between pitch and (fundamental) frequency?

A number of earlier studies suggest that this is actually not exactly the case, specifically that the pitch of a pure tone can depend weakly on its level, a finding that is not straightforward to explain with standard theories of pitch (Licklider, 1951; Terhardt, 1974a). According to Stevens' rule (Stevens, 1935), the pitch of low-frequency pure tones (<500 Hz) decreases with increasing level while the pitch of high-frequency pure tones (>4000 Hz) increases with increasing level. This finding was obtained by a relatively indirect method, mainly with one subject, in which two tones of different frequencies were presented and the subject was instructed to change the second tone's level so that the two pitches matched. A similar finding for low frequencies was mentioned by Fletcher (1934) and shown with another method by Snow (1936), who asked subjects to rank two tones of different levels and frequencies as higher or lower in pitch; a lack of effect on complex tones was also mentioned (but not shown). These results were later confirmed with more subjects (Morgan et al., 1951; Terhardt, 1974b, 1975), although with substantial inter-individual variability, using a pitch matching method – the subject adjusted the frequency of the second tone to match the pitch of the first tone. At 200 Hz, when the tone level was increased from 40 dB to 80 dB SPL, the pitch shifted down by an amount equivalent to about half a semitone (Terhardt, 1974b), well above the just noticeable difference (for tones of identical level). This was confirmed more exhaustively

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with two subjects by Verschuure and van Meeteren (1975). Terhardt (1975) reported small pitch shifts with complex tones, but the shifts varied markedly across participants, and the statistical significance of the shifts was not assessed.

The goals of this psychophysical study were (1) to show that the reported changes with level truly reflect the level dependence of melodic pitch (as opposed to procedural biases or confusion of the perceptual dimensions of pitch and loudness); (2) to determine the level dependence of the pitches of pure tones and complex tones with identical fundamental frequency; (3) to determine whether the phenomenon is influenced by musical experience. Using pitch- and interval-matching experiments, we found that the pitch of low frequency pure tones, but not complex tones, depends on level regardless of musical experience, and that the measured phenomenon reflects small but actual changes in melodic pitch that partially transfer to the perception of melodic intervals.

2. Materials and methods

2.1. Subjects and equipment

Ethical approval was granted by the local ethics committee (Comité pour la Protection des Personnes Ile de France). All subjects were fully informed about the goal of the study and provided written consent before their participation. All subjects had normal hearing (<20 dB hearing loss (HL) between 100 and 8000 Hz), and were 18–35 years old. Subjects in the non-musician group had never played an instrument or only briefly played one (<2 years) during childhood. Subjects in the musician group had 7–22 years of musical training, and played at least 1 h per day at the time of the experiments (Table 1). Experiments 1 and 3 included 4 non-musicians and 4 musicians; experiment 2 included 2 musicians and 2 non-musicians from the same pool; experiment 4 included 6 other musicians.

Stimuli were generated digitally at a sampling rate of 44.1 kHz. Stimuli were presented diotically via a RME Fireface UC soundcard and a Sennheiser HD580 headphone. Sound levels were calibrated for each tone frequency with a sound pressure level meter, giving estimated sound levels at the eardrum. Subjects were seated individually in a double-walled, sound-insulated booth.

2.2. Experiments 1 and 2: pitch matching of pure tones

Each trial began with a 500-ms reference pure tone followed by a 300-ms gap and a 500-ms comparison tone. Listeners were asked to adjust the frequency of the comparison tone until its pitch matched that of the reference tone. The starting frequency of the comparison tone was randomly chosen from a uniform distribution on a discrete semitone scale with a range of 4 semitones around the frequency of the reference tone. After each trial, listeners could adjust the frequency of the comparison tone up or down by 2, 0.5 or 0.125 semitones, without exceeding ± 4 semitones around the reference frequency, could elect to hear the same tone pair again, or could indicate that they were satisfied with the pitch match. Listeners were encouraged to start with a big step size and then change to a smaller step size, and to adjust the comparison tone below and above the chosen frequency before making a final decision. No feedback was provided. The reference pure tone had a frequency of 200, 1000 or 4000 Hz. The level of reference tone varied from 20 to 70 dB SPL in steps of 10 dB. In experiment 1, the level of comparison pure tone was set to 40 dB SPL. In experiment 2, it also varied from 20 to 70 dB SPL. Each combination of reference and comparison levels was presented 10 times.

For experiment 1, the comparison level was fixed, while reference levels and frequency conditions were randomized between trials. For experiment 2, comparison levels were randomized across listening sessions. In each listening session, the comparison level was fixed but reference levels and frequency conditions were randomized. Each session contained 18 different conditions (6 reference levels times 3 frequency conditions), and lasted 5–20 min depending on the subject. Experiment 1 consisted of 10 sessions per subject (i.e., 10 trials for each condition), while experiment 2 consisted of 60 sessions per subject (6 comparison levels times 10 trials) – on average about 10 h in total per subject.

Table 1
List of subjects and their musical experience.

Subject	Age	Sex	Musical experience	Experiments
SAG	22	M	Drums, 12 years	1, 3
PES	22	F	None	1, 2, 3
PSS	25	M	None	1, 2, 3
PAM	22	F	Piano, 14 years	1, 2, 3
PJC	33	M	Guitar, 15 years	1, 2, 3
PTC	24	F	Trumpet, 15 years	1, 3
PAL	20	M	None	1, 3
SYZ	33	F	None	1, 3
LHK	27	F	Piano and violin, 10 years	4
PPG	27	M	Violon, 7 years	4
SLC	21	F	Violin, 15 years	4
SLJ	20	M	Piano, guitar and saxophone, 10 years	4
SEC	28	F	Violin, 22 years	4
SOP	23	M	Trumpet, 10 years	4

2.3. Experiment 3: pitch matching of harmonic complex tones

The pitch-matching procedure was the same as for Experiment 1, except that both the reference and comparison tones were harmonic complex tones, composed of 6 or 12 consecutive harmonics (order 1–6 or 1–12) with equal amplitude and random phase. The level of the comparison tones was fixed at 30 dB SPL per component (overall level was thus 37.8 or 40.8 dB), and the level of reference tones was varied from 10 to 60 dB SPL per component. The initial fundamental frequency of the comparison tone was randomly chosen from a uniform distribution on a discrete semitone scale with a range of 4 semitones around the fundamental frequency of the reference tone (200, 1000 or 4000 Hz).

2.4. Experiment 4: pitch interval matching

An interval consisted of a pair of 500-ms pure tones presented in sequence (no gap). Each trial began with a reference interval, followed by a 300-ms gap and then a comparison interval. The resulting sequence of 4 tones always increased in frequency. Subjects were instructed to adjust the frequency of the last tone of the comparison interval until its pitch interval matched that of the reference interval, with the same procedure as in the pitch-matching experiments. To prevent listeners from memorizing the reference interval, its size was set to 2 or 3 semitones with equal probability. To ensure that listeners were performing the task by comparing intervals rather than the pitches of individual tones, the frequency of the first tone of the reference interval was set randomly at 200 Hz $\pm$ 3 semitones (uniform distribution on a semitone scale), and the frequency of the first tone of the comparison interval was set randomly between 0 and 3 semitones above that of the second tone of the reference interval. The levels of the two tones in the reference pair were as follows: (1) increasing level, 40 dB SPL then 70 dB SPL; (2) decreasing level, 70 dB SPL then 40 dB SPL; (3) fixed level, 55 dB SPL then 55 dB SPL. The level of the two tones of the comparison interval was fixed at 55 dB SPL.