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Intonation of Harmonic Intervals: Adaptability of Expert Musicians to Equal Temperament and Just Intonation

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This study examines the deviation in the intonation of simultaneously sounding tones under the condition of an embedded melody task. Two professional musicians (trumpet players) were chosen as subjects to play the missing upper voice of a four-part audio example, while listening via headphones to the remaining three parts in adaptive five-limit just intonation and equal temperament. The experimental paradigm was that of a controlled varied condition with a 2 (tuning systems) × 5 (interval categories) × 5 (renditions) × 2 (players) factorial design. An analysis of variance showed a nonsignificant difference between the average deviation of harmonic intonation in the two systems used. Mean deviations of 4.9 cents (SD = 6.5 cents) in the equal-temperament condition and of 6.7 cents (SD = 8.1 cents) in the just-intonation condition were found. Thus, we assume that the musicians employed the same intonation for equal-temperament and just-intonation versions (an unconscious "always the same" strategy) and could not successfully adapt their performances to the just-intonation tuning system. Fewer deviations could be observed in the equal-temperament condition. This overall tendency can be interpreted as a "burn in" effect and is probably the consequence of long-term intonation practice with equal-temperament. Finally, a theoretical model of intonation is developed by use of factor analysis. Four factors that determine intonation patterns were revealed: the "major third factor," the "minor third and partials factor," the "instrumental tuning factor," and the "octave-minor seventh factor." To summarize, even in expert musicians, intonation is not determined by abstract tuning systems but is the result of an interaction among compositional features, the acoustics of the particular musical instrument, and deviation patterns in specific intervals.

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> "On brass instruments . . . equal tempered intonation is unattainable"
> Vogel (1961, p. 97)

In recent years, a distinction has been made between tuning (an idealized system of pitch relation, such as just or equal tempered tuning) and into-

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nation (the performer's responsibility to play in tune). Support for this distinction comes from Seashore (1938/1967, p. 218) and Oldham (1980, p. 279). Following these authors, intonation during a performance is influenced by the melodic structure of a piece, the performer's expertise, and the particular instrument. Although theoretically the fundamental problem of temperament is relevant, in practice the performer's musicianship and technique are usually overriding factors. Thus, intonation refers to the skillful ability of playing in tune. In the context of a real performance situation (e.g., a player accompanied by an ensemble), the player presumably uses all acoustical information available to manage the challenges of this task. Unlike a standard performance situation, artificial stimuli used in laboratories may be unfamiliar to the subjects. It is therefore not surprising that most studies find that musicians' tolerance to mistuning ranges from about 10 to 50 cents. However, it remains uncertain which factors could influence intonation in more realistic experimental situations.

The first important factor is the influence of spectral information. For example, in Greer's (1970) study, the largest differences were observed when subjects played together using an unfamiliar timbre such as an oscillator (+70 cents) or an organ (+22 cents), whereas the smallest differences were associated with the use of the familiar timbre of wind instruments (+10 cents). In another study, Vos (1984) found that for fifths and major thirds the interference of the first pair of noncoinciding harmonics was important for beat discrimination. Also, discrimination thresholds were somewhat higher for major thirds than for fifths, and spectral interferences produced by higher harmonics were relevant for major thirds.

The second important factor is the perceptibility of mistuning. Williamson (1942) claims a threshold as low as 2 cents; Madsen, Edmonson, and Madsen (1969) find a threshold of about 10 cents. Vos (1982) verified that other factors could influence pitch discrimination because of beat frequency and interval size in simultaneously discerned, mistuned (compressed and stretched) harmonic intervals, such as major thirds and fifths. Discrimination thresholds were found to be higher in these intervals. The deduction that a varying sensitivity to mistunings is dependent on interval categories is supported by the experiments described in Vos (1986). Vos (1982) revealed different identification thresholds for the direction of mistuning. His data showed that an identification threshold of between 20 and 25 cents exists for fifths and major thirds, with no significant differences between interval categories. Such a threshold seems quite high, and one should assume that the results collected in a laboratory experiment with nonexpert listeners and isolated intervals cannot be directly applied to the expected behavior of a musician who plays a piece of music under the constraints of real-time performance. The perception of mistuning of varying degrees is not simply a question of psychoacoustics but also has a considerable influence upon aesthetic appreciation. For example, Vos (1988) demonstrated that tuning versions were better evaluated (in the sense of an "overall acceptability") with decreasing mean degrees of tempering. Finally, Burns (1999, p. 220) summarizes the general trends in adjustment experiments: they (a) show a day-to-day variability in intrasubject judgments, (b) show a significant intersubject variability, and (c) show a tendency to compress smaller and stretch larger intervals.

The Rationale of the Study

As is shown in previous literature, intonation is influenced by numerous variables, such as the instrument's imperfections, musical context, playing conditions (solo or accompanied), timbral spectrum, register, dynamics, player idiosyncrasies, beat frequencies, tone durations, and the size of intervals. These influential factors can be classified as bottom-up factors (e.g., beats) or top-down factors (e.g., musical context). A bottom-up approach supposes that information is driven by the stimulus, whereas a top-down approach implies a schema-based information processing where higher level processing plays an important role. Most studies on intonation implement bottom-up approaches (e.g., Burns, 1999, p. 258), whereas our study follows a top-down approach that considers, for example, the "human factor" (the performer). Yet, bottom-up factors will also be discussed, as will possible interactions between the two perspectives.

Our study is based on the hypothesis that the ability to play in tune and to adapt to a tuning system is superior to and shows less variability than the discrimination thresholds of 10-30 cents reported in previous studies. Our assumption is based on the use of several acoustical cues such as timbre, context, or beats, which are available only in a standardized experimental condition that simulates an ensemble. Only under such realistic conditions can conclusions be drawn regarding the player's intonation adaptability to a given tuning system.

Approach of This Study and Research Questions

A top-down approach was used in this study, in an attempt to allow the researchers to gain deeper insight into harmonic intonation characteristic of an ensemble situation. First, the top-down approach was intended to reduce the influence of the composition's expressive features on intonation through the use of a specifically designed test composition in which expression was reduced to a minimum. Second, the paradigm used was that of an ensemble situation in a realistic performance setting with realistic constraints imposed by an ongoing accompaniment. Third, the ensemble timbre, as an important source of acoustical cues for intonation adaptation, was used to simulate a familiar performance situation. Finally, the context of the performance situation was varied systematically through the use of different tuning systems in order to investigate the adaptability of the performer.

A theoretical framework for the hypothesized effect of practice on the adaptability and control of intonation methods is provided by expertise theory, which assumes that experts possess a high degree of adaptability in relation to different task constraints (e.g., different tuning systems). Although numerous studies have investigated ensemble intonation (e.g., in a string quartet; for extensive surveys see Fischer, 1996; Burns, 1999, p. 245), no studies have actually been carried out using controlled, varied conditions. Perfect task adaptation should result in a nonsignificant difference between the mean deviations performed using both tuning conditions.

In sum, the current study addresses the following questions:

- How can a musician cope with the technical limitations of an instrument while adapting to a given tuning/temperament?
- How reliable is intonation when comparing different renditions of the same piece?
- How do individual players differ in terms of sensitivity to different degrees of mistuning (see Vos, 1986)?
- How important is expertise for successful adaptation to tuning/temperament changes in the accompaniment?
- Is there any evidence of “tonal gravity” (Fyk, 1995), causing “islands of intonation stability,” or is it possible to observe overall stability, independent of the different interval categories?

Method

MATERIAL

A paradigm of a controlled varied testing condition was used with a 2 (tuning systems) × 2 (players) × 5 (renditions) × 5 (interval categories) design, which will be explained in the following section. A short piece of music was composed that met the following criteria:

- Limited expressive melodic movement and intention.
- A slow tempo to enable the player to listen to and adjust his intonation (Vos, 1982, reveals that the discrimination threshold of slightly mistuned intervals decreased with increasing stimulus duration > 250 ms). Additionally, a slow tempo delivers signal durations leaving a sufficiently long quasi-stationary part of the note.
- Technical simplicity to render the player free from technical obstacles and prevent fatigue on repeated renditions.
- A four-part structure to simulate an ensemble timbre over which the subject could play the upper part (embedded interval paradigm).

- An A-B-C form with modulation in the B section to test the subject's adaptation to harmonic changes.
- Chordal progression in root position only to make identification of the harmonic context easier.
- Concentration on only a few test intervals such as the octave, minor third, major third, fifth, and minor seventh.

The test composition is given in Figure 1 with its formal structure determined by three harmonic sections: part A (bars 1–4) is in the key of E♭ major, part B (bars 5-8) is in c minor, and part C (bars 9–12) starts in G major and modulates back to the tonic of E♭ major, with all modulations occurring through secondary dominants. In the next step, two three-part tuning versions were generated from the original MIDI file: version (a) using equal temperament (ET) and version (b) using five-limit just intonation (J5).[1] The software RealTimeTuner (Version 1.2) by William Cooper (Cooper, 2000) was used for the generation of the J5 version. This software uses pitch-bending information from the MIDI format for retuning. The software option "automatic chord following" was used, which corresponds to so-called adaptive just tuning. This means that the software continually scans all currently sounding notes for triads and seventh chords. Whenever one is detected, the system is instantly retuned to the chord's root. As a result, the current tonic key remains until a different chord is detected and all

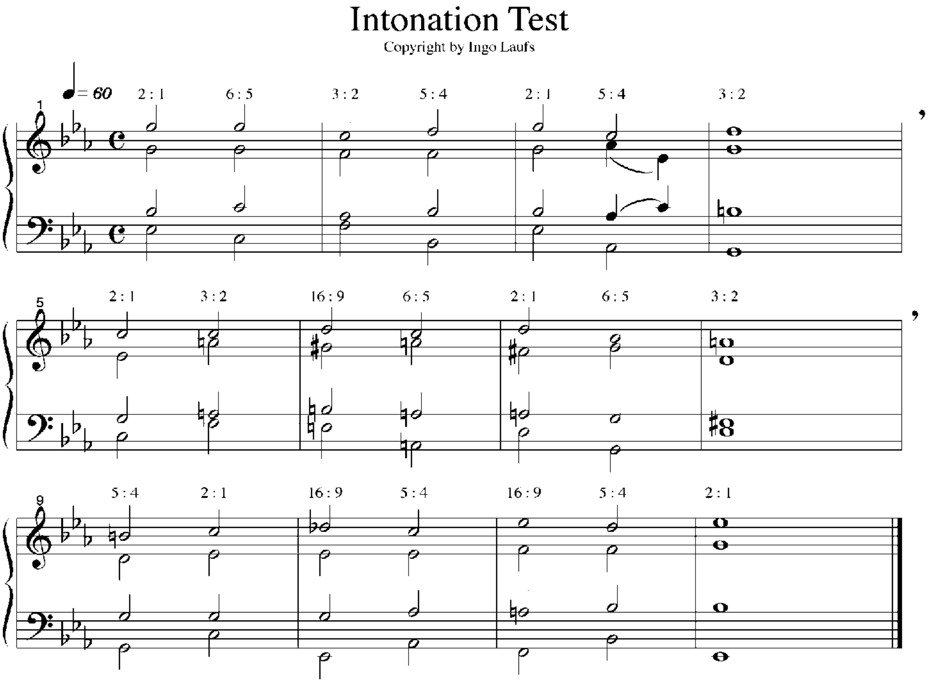

Fig. 1. Composition used in the experiment. Proportions indicate frequency ratios between the bass and melody notes of a chord, used in just intonation.

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[1] Sound examples for this experiment can be downloaded from the following web site: http://musicweb.hmt-hannover.de/intonation/.

harmonies sound as pure as possible in beat-free just intonation from chord to chord (for intonation details, see Blackwood, 1985).[2]

Great care was taken to ensure a high-quality stimulus material.[3] In the final phase, sound files for CD recordings were generated from the MIDI files using a Yamaha Sampler (TG 77) with a "French horn" timbre. Because of the widely distributed use of orchestral pitches higher than A = 440 Hz, a decision was made to raise the pitch of the sampler to A = 442.5 Hz, which corresponds to an increase of 10 cents. This lies in the mid-range of the orchestral pitches and corresponds to the general tendency during the past few decades of raising standard pitch (Rhodes & Thomas, 1980, p. 785). For example, the Pittsburgh Symphony Orchestra uses a standard pitch of 442 Hz, the New York Philharmonic Orchestra uses a pitch of 441.5 Hz, and the Berlin Philharmonic Orchestra uses a pitch of 445 Hz. In a recent study, Haynes (1998, p. 1828) observed a trend toward higher pitch with a mean of 445 Hz (no raw data indicated) and a maximum of 450 Hz. The value of 442.5 Hz was also recommended by one of the subjects of this study (Subject P), whose orchestra uses this tuning pitch.

Two tuning versions were produced: version (a) was based on a so-called five-limit just tuning system and version (b) on a 12-tone equal temperament system. The character of five-limit tuning is explained by Monzo (1998) as "a pitch system in Just Intonation where all ratios are of integers containing no prime factors higher than n is said to be an '*n*-limit' system. . . . When unqualified, 'just intonation' generally means a 5-limit tuning. . . . Systems with a higher limit are frequently called extended just intonation. 3-limit just intonation systems are generally called 'Pythagorean.'" An example shows the consequences of n-limit choice for the calculation of interval sizes: the major third would be calculated in Pythagorean three-limit tuning by the ratio of 81:64. This results in a wide and beating major third that is about 8 cents higher (= 408 cents) than the equal tempered third. In five-limit tuning, the major third would be calculated on the basis of the prime number 5 as 5:4. This results in a pure third of 386.3 cents, which is 13.7 cents lower than the equal tempered interval. Subsequently, the minor sevenths (as contained in dominant seventh chords) would be 996.1 cents, which is 3.9 cents lower than the equal tempered interval. If a decision was made to use a seven-limit system, the same interval would be calculated from the ratio of the so-called "natural" or "harmonic" seventh (7:4), which has an extremely narrow sound (-31.2 cents), resulting in an interval size of 968.8 cents. Owing to its complex intervallic proportionality of 7:4, this seventh is not used in ensemble situations.

SUBJECTS

Because of the need for variability of intonation, familiarity with ensemble playing, and the availability of a recommended expert with outstanding skills, the trumpet was considered the most suitable choice of instrument for the study. Two trumpet players took part in this experiment. Player S (semiprofessional, 24 years old) was a trumpet student at a music

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[2] An example of this option would be the note A as a major third above F, which has a different function as the fifth above D, resulting in a minor chord on the second scale degree in the key of C with a compressed fifth. Under this condition, the progression of bass note fundamentals takes place in equal tempered steps. The application of these options ensured the sound result to be as beat-free and pure as possible. Additional software-based solutions for adaptive tuning have recently been developed, and documentation can be found on the following web sites: http://www.justonic.com, http://www.adaptune.com, and http://tigger.cc.wmich.edu/~code/groven/.

[3] In fact, pitch analysis of detuned samples showed that the combination of MIDI files detuned by pitch-bending information produced acoustical signals with the following characteristic: mean frequency resolution in the vicinity of the upper voice = 0.3 Hz (*SD* = 0.29 Hz). In relation to the frequency range of the upper voice, this resulted in a frequency resolution of 0.8 cents for the highest melody note (*SD* = 0.8 cents) and of 1.17 cents for the lowest melody note (*SD* = 1.13 cents).

academy and had been playing for 15 years. His additional monthly ensemble activities added up to 6-10 hours, depending upon seasonal activities. Subject P (professional, 39 years old) was a trumpet player in a symphony orchestra and had been playing for 19 years professionally (28 years total). His additional monthly ensemble activities added up to 15-20 hours, mostly in an ensemble for avant-garde music. Subject P was recommended by a conductor because of his outstanding intonation skills.

PROCEDURE

Ten days before the recording session, subjects received a CD containing different versions of the test composition: (a) the three-part test-composition in ET (without upper voice), and (b) a three-part rendition in J5, and a repeated test tone (E♭) to which instruments could be tuned. Subjects also received the score with the solo voice and an explanation of the task. The following main instruction was also given: "The accompaniment of the following samples is in just intonation (J5) or in equal temperament (ET). Please play in J5 or ET and try to perform the most suitable adaptation to the indicated test composition on the CD." Subjects were asked to record both the amount of time taken as well as the valve positions used for practicing during the 10-day preparation phase.

The ensuing recording session took place in each subject's home, where subjects listened to the three-part accompaniment through open headphones and performed the upper voice. The recording was carried out with a DAT recorder using a microphone (Sennheiser E 608) attached directly to the instrument's bell. Subjects played their own instruments (modern valve trumpets in B♭) and recorded five renditions in each tuning system with short breaks in between. Total session length approximated 1 hour.

Additionally, in order to assess the subject's perceptual skills, an aural test consisting of a cadence in three tuning systems was conducted: (a) Pythagorean, (b) equal tempered, and (c) just intonation. Subjects were asked to identify the correct tuning system on six consecutive trials given after a short trial section.

Results

First, we will analyze the perceptual test; then we will discuss the general intonation tendencies of interval categories of the players individually and in repeated renditions. Finally, we will investigate the interaction among these factors and compare the observed intonation with a theoretical model of intonation.

PERCEPTUAL TEST

Our first analysis examined performance in the listening test. Subjects recognized the cadential sequences presented in the perceptual test perfectly. This ceiling effect suggests that the aural abilities needed to distinguish the three tuning systems were intact and perfectly trained.

GENERAL TENDENCIES OF INTONATION

For analysis, the solo voice recordings were sampled onto hard disk (sample rate = 11.025 kHz), and frequency analysis of each of the 21 notes was done by using the software Praat (Boersma, 2000, Version 3.8.16).

The first and last 200 ms from each note were removed so that only the quasi-stationary part of each note with a duration of 1.6 s was analyzed (see Fyk, 1995, p. 65). A "periodicity" module was chosen with a fast Fourier transform size of 16.384 points. This resulted in a frequency resolution of 0.67 Hz, corresponding to a small smallest difference of 1.4 cents in the vicinity of 622 Hz ($E\flat_5$). Each player performed 210 notes for the five renditions in two tuning contexts. Table 1 shows the results of pitch analysis for the performed tones in both tuning systems. Table 2 contains the corresponding statistical values. A second analysis used a repeated measure design (GLM) with tuning (2), interval (5), and rendition (5) as repeated measures and player (2) as a between-subjects factor.

Factor "Tuning"

The first factor, Tuning, showed an insignificant difference between the two systems ET and J5, $F(1,4) = 0.29$, $p = .61$. Performance in ET was

TABLE 1
Theoretical and Mean Performed Interval Sizes in Cents

	Equal Temperament		Just Intonation	
Interval	**Theoretical**	**Observed**	**Theoretical**	**Observed**
Minor third	300.0	309.2	315.6	310.5
Major third	400.0	402.0	386.3	402.3
Fifth	700.0	707.7	702.0	708.4
Minor seventh	1000.0	1001.7	996.1	1003.1
Octave	1200.0	1204.8	1200.0	1205.0

TABLE 2
Means and Deviations for Two Tuning Systems and Five Interval Categories Over Five Renditions (All Values in Cents)

Tuning	Interval	n	Mean	*SD*	Min.	Max.
Equal temperament	Minor 3	30	9.2	5.8	-1.3	20.1
	Major 3	50	2.0	5.6	-10.0	14.1
	Fifth	40	7.7	5.3	-5.0	16.8
	Minor 7	30	1.7	7.8	-11.1	21.1
	Octave	60	4.8	5.7	-5.5	19.5
	Total	210	4.8	6.5	-11.1	21.1
Just intonation	Minor 3	30	-5.1	4.2	-12.4	3.0
	Major 3	50	16.0	4.1	5.6	23.1
	Fifth	40	6.4	4.6	-4.1	13.7
	Minor 7	30	7.0	7.6	-10.0	19.2
	Octave	60	5.0	4.9	-7.4	15.6
	Total	210	6.7	8.1	-12.4	23.1

characterized by a mean overall deviation of 4.8 cents (*SD* = 6.5 cents) and in J5 by a mean of 6.7 cents (*SD* = 8.1 cents) (see also Figure 2). These results represent very small mean deviations from the ideal adaptation. As the researcher was interested in the null hypothesis between mean deviations, it was necessary to achieve an alpha error level greater than .20 in order to avoid the beta error. Our findings show that differences in adaptation to the varied tuning contexts of ET and J5 are insignificant, yet the question remains whether subjects can adapt perfectly to one of the given tuning systems.

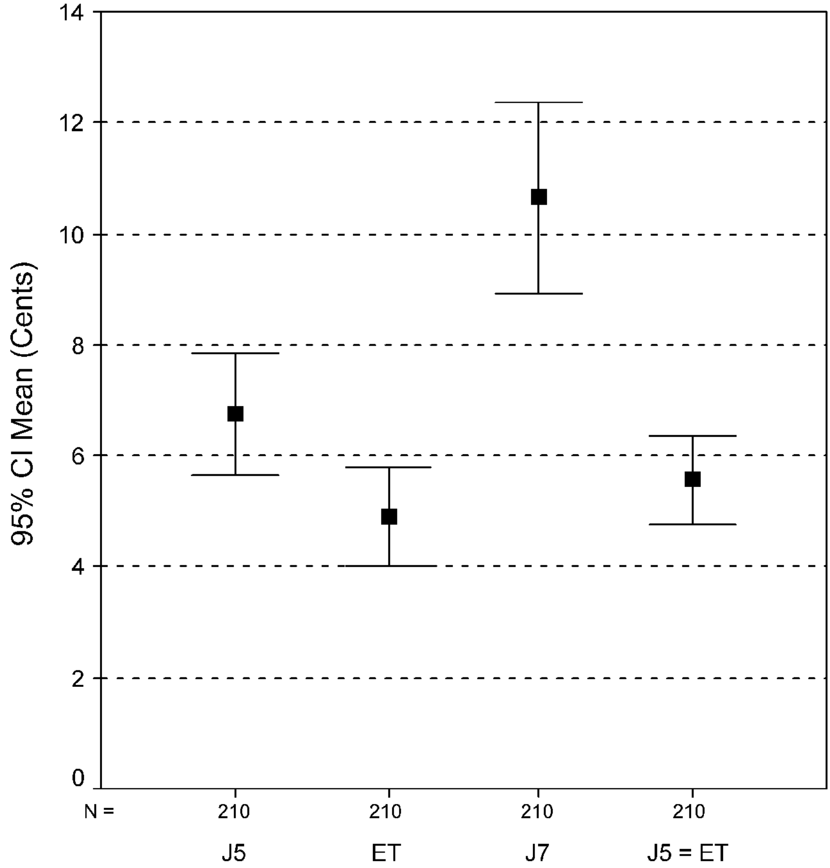

Fig. 2. Overall deviations in tuning adaptation. "J5" means that the accompaniment was in just intonation. The category "J5 = ET" shows deviation on the assumption of a simple intonation transfer strategy from condition J5 to ET. The category "J7" represents deviation based on the hypothetical use of a seven-limit tuning system of the subjects. The seven-limit system is characterized by a strongly compressed 7:4 "natural" seventh of 968.8 cents (= -31.2 cents compared with an equal-tempered minor seventh). The zero line on the vertical axis represents perfect adaptation to each tuning system with zero deviation. N on the horizontal axis denotes the pooled number of performed intervals. Error bars indicate confidence interval (CI) of average intonation deviation.

Transfer Strategies Between Tuning Systems

A simple explanation for the result of an insignificant difference between the two systems was found by looking at possible transfer strategies of intonation from ET to J5: deviations were calculated under the assumption that the same intonation strategy would be used in both ET and J5. This means that players were not able to perform the task according to the two tuning systems. Subsequent analyses revealed a mean deviation in the renditions as shown in the right error bar (category "J5 = ET") of Figure 2. In this case, the baseline of the category J5 = ET represents the values as expected for ET. Figure 2 shows that this hypothetical intonation strategy would produce only slight differences in intonation (mean = 5.5 cents, *SD* = 5.8 cents) in comparison to the pattern observed for ET intonation. As it was not known in advance which minor seventh would be used in the performances,[4] we tested whether calculations on the basis of a seven-limit system (J7) would produce different results from those based on the three other systems. As Figure 2 shows, the assumption of a seven-limit system produced the largest mean deviations (mean = 10.66 cents, *SD* = 12.68 cents). Analysis of variance showed a significant overall difference among the four possible tuning systems, $F(3,12) = 33.79$, $p = .00$. Paired comparisons showed that calculation of the mean deviation on the assumption of a J7 strategy, with a compressed minor seventh of 968.8 cents, differed significantly from the other three systems ($p = .00$). Mean deviations between the systems of J5, ET, and J5 = ET did not differ significantly from one another. These results rule out the possibility that intonation is based on an implied J7 system. Calculation of the mean deviation on the basis of the 9:5 stretched seventh (1017.6 cents) can also be excluded because subjects received information that intonation in the J5 condition was supposed to use compressed sevenths. However, it should be pointed out that such a result is hardly surprising because the very strong compressed minor seventh is unusable in orchestral playing and is rarely used by trumpeters.

These results should be interpreted along with the average differences between the tuning systems of ET and J5. Under the assumption of perfect tuning adaptation, the mean nominal difference of performances of the test composition was characterized by an amount of 6.4 cents, with a minimum of -13.7 and a maximum of 15.6 cents. This means that in our test composition, a simple "always the same" transfer strategy from ET to J5 would have indeed produced acceptable renditions with only slight mean differences in intonation. Nevertheless, the small mean deviations between ET and J5 (as shown in Figure 2) indicated that subjects tried to use differ-

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[4] Three possibilities exist within the five-limit system; the stretched 9:5 interval being 1017.6 cents, the slightly compressed 16:9 interval being 996.1 cents, and in seven-limit tuning the strongly compressed "natural" 7:4 interval being 968.8 cents.

ent intonation strategies. However, results for the J5 version calculated under the assumption of a deliberate adaptation to this system produced higher deviation than had been expected in the case of a simple transfer behavior. In this latter case, performed pitches in the condition J5 were calculated as deviations from the baseline of ET.

Factor "Interval"

An analysis of variance indicated no significant overall differences in the factor Interval, $F(4,16) = 2.16$, $p = .35$, but revealed a significant tuning × interval interaction, $F(4,16) = 21.66$, $p = .00$ (see Figure 3 and Table 2). Figure 3 reveals that there are differences and similarities within and between interval categories of the two tuning systems. The starting point was the analysis of intonation differences of intervals within the tuning systems

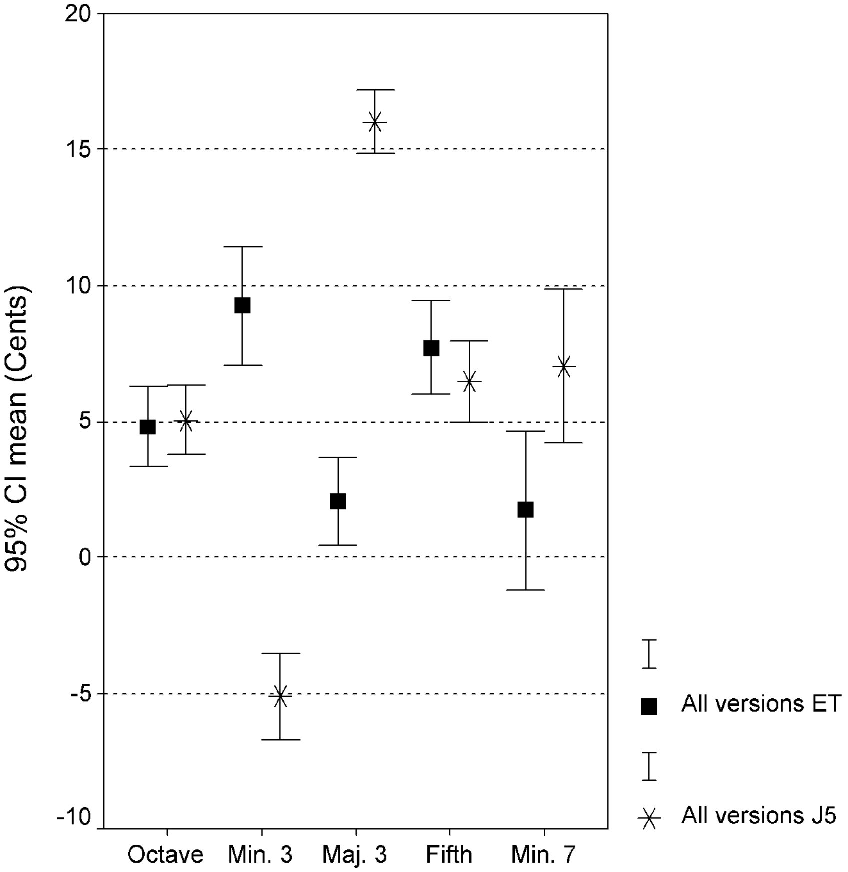

Fig. 3. Interaction between tuning systems and interval category. Error bars indicate confidence interval (CI) of average intonation deviation.

ET and J5. On the basis of a post-hoc Scheffé test for Table 2, it can be clearly shown that intonation adaptation in ET is best achieved in the octave, the major third, and the minor seventh. No significant differences exist when comparing the deviations of these intervals. Their intonation in ET is characterized by a deviation of less than 5 cents and reaches a mean value of 1.7 cents for the minor seventh (*SD* = 7.8 cents). Larger deviations can be observed for the minor third (mean = 9.2, *SD* = 5.8 cents) and fifth (mean = 7.7, *SD* = 5.3 cents), but with a mean deviation of less than 10 cents. No significant differences exist between the intonation of minor third and fifth; however, differences are significant between the fifth and minor seventh in ET. In summary, there seem to be two groups of intervals in ET that differ judging by their amount of intonation deviation: Group 1 (large deviation) consisting of the minor third and fifth, and Group 2 (small deviation) consisting of the octave, major third, and minor seventh.

The analysis of deviations between interval categories within J5 produced a different pattern of intonation: only intonation deviation for octaves and minor thirds lies within the boundary of 5 cents. Major thirds in particular are characterized by a stretched intonation (mean = 16.0, *SD* = 4.1 cents). All differences in J5 are significant, except those between the categories of octave, fifth, and minor seventh. The author's initial explanation for the observed intonation deviations is based on the assumption of a transfer strategy between tunings: in J5, a minor third should have a difference of +15.6 cents compared with ET. Hence, as one can observe in Figure 3, minor thirds in ET are performed about 10 cents; stretched and unadapted minor thirds would reach a deviation of about 5 cents if calculated on the basis of a J5 system. If one tries the same explanation for major thirds respective to minor sevenths, one gets very close to values predicted by a transfer strategy. Major thirds should be 13.7 cents lower in J5 than in ET; however, if played without successful adaptation, they should deviate by the same amount when transferred from J5 to ET. This prediction is confirmed by the values in Table 2 for major thirds and minor sevenths (minor sevenths of 16:9 should be 3.9 cents lower in J5 than in ET). Intonation deviations of intervals between ET and J5 showed that significant differences between the two tuning systems exist in the categories of major and minor thirds and of the minor seventh ($p < .01$).

The most astonishing result is the very small overall deviation, with a mean amount of less than 10 cents in ET. This is surprising because the ET system gives no "natural" acoustical cues, such as a specific number of beats for intonation adaptation, and can only be practiced with an equal-tempered reference instrument such as the piano. This is exactly what the subjects did in their 10-day preparation phase, and the extensive performance experience with the ET system required to perform in a symphony orchestra supports the optimal adaptation to ET. Despite differences in performance experience between players, Figures 4a and b clearly indicate

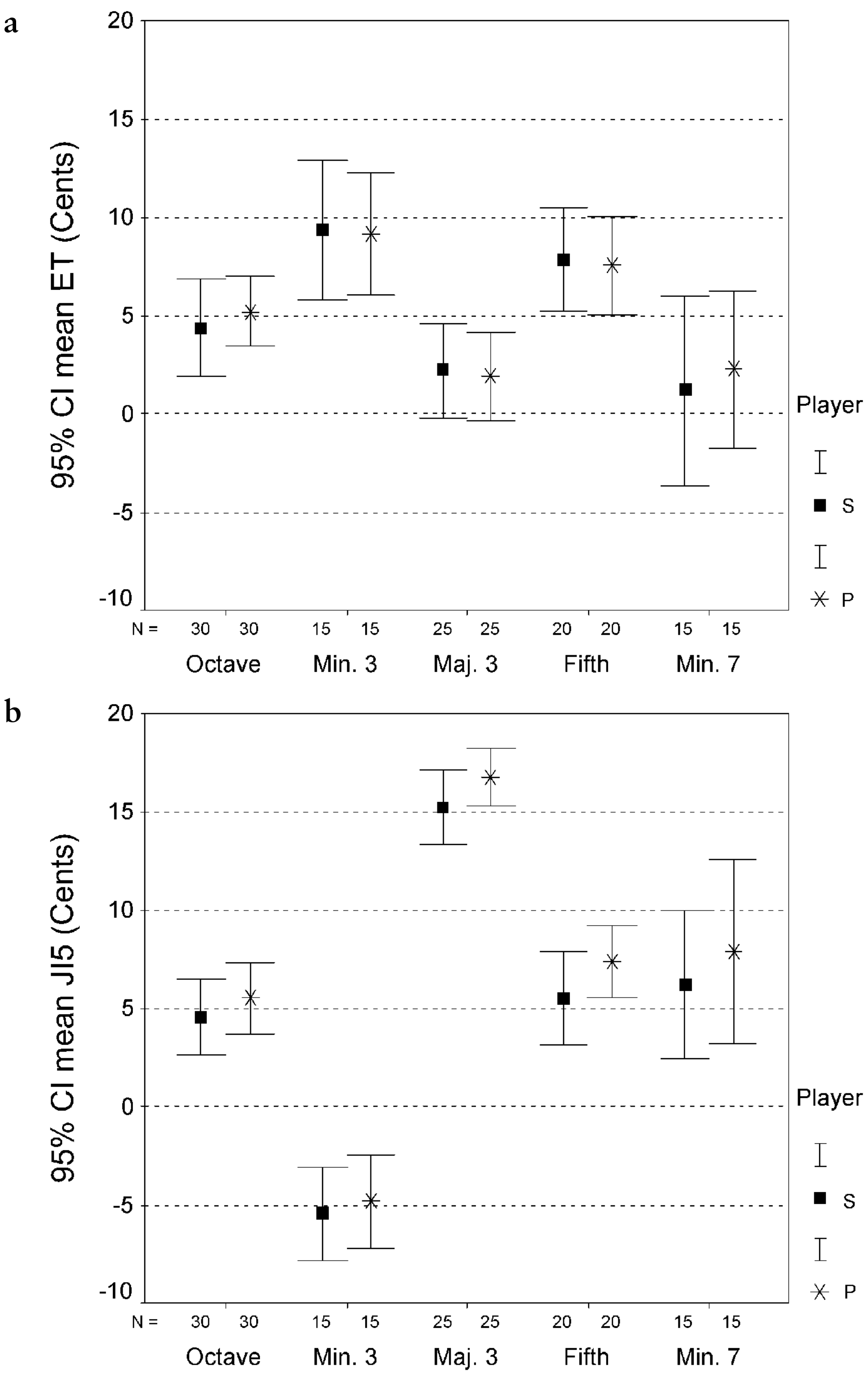

Fig. 4. Interaction between intervals and subjects within two tuning systems: (a) equal temperament (ET), (b) just intonation (J5). Player S is a semiprofessional; Player P is a professional. N on the horizontal axis denotes the pooled number of performed intervals. Error bars indicate confidence interval (CI) of average intonation deviation.

that the same intonation tendencies exist in both players and in both tuning systems. In Figure 4b, both players' intonation can be characterized by the same deviations in J5, which is congruent with the results shown in Figure 3, supporting our assumption of an intonation transfer strategy for both players. On the Tuning × Player × Interval level, all differences could be explained by the assumption of an intonation transfer.

Factor "Player"

Since the factor Player showed no overall differences in tuning adaptation, $F(1,4) = 0.29$, $p = .61$, one can assume that both players used a transfer strategy. The general tendency was observed to maintain positive average deviations (despite rare negative deviations of certain intervals), thus indicating that intervals were tuned higher than their nominal values. It was assumed that subjects used a higher basic frequency than given in the sample tone (E♭) at the beginning of the recording session. Measurement of the sample tone frequency showed a frequency of 626.4 Hz for E♭, which is about 10 cents higher in relation to the standard pitch of A = 440 Hz. Pitch analysis of the subjects' original tuning revealed a frequency of 627.8 Hz for Player P (3.8 cents higher than the given tuning tone) and of 629.9 Hz for Player S (9.6 cents higher than the given tuning tone). The subjects tended to use higher pitches when tuning despite the raised base pitch of the sample CD (+10 cents). This could be caused by the "déformation professionelle," whereby the players increased pitch (or intonation) an additional 10 cents compared with the already raised pitch of 10 cents in our sample CD to match an orchestral pitch of 445 Hz. Moreover, the experimental situation might have influenced the intonation by increasing the players' mental tension, thus affecting embouchure (lip tension).

Factor "Rendition"

The effect of renditions on changes in intonation is more complicated because of the interaction of this variable with other variables in general. Renditions showed no influence on changes in intonation, either as an overall effect, $F(4,16) = 2.03$, $p = .13$, or in interaction with the factor tuning system, $F(4,16) = 2.84$, $p = .12$.

Interactions Between Factors "Player," "Tuning System," "Interval Category," and "Rendition"

The analysis of interactions between factors showed that no single factor can give a sufficient explanation for our findings. For example, players showed differences between renditions, $F(4,16) = 3.36$, $p = .03$, as well as between various renditions in different tuning systems, $F(4,16) = 4.27$, $p =$

.02, and between various interval categories in different renditions, $F(16,64) = 2.51$, $p = .00$. Player S (semiprofessional) increased his deviation from the first rendition (mean = 5.1 cents) to the fifth rendition (mean = 7.4 cents), whereas Player P (professional) remained constant (first: mean = 6.3, fifth: mean = 6.6 cents). From the perspective of tuning conditions, the optimum performance from Player S in ET was his first rendition (mean = 4.2 cents), and he became steadily less accurate toward the fifth rendition (mean = 8.2 cents) but remained constant for all five renditions of J5. A contrasting account can be observed in the performances of Player P: in the first rendition, his performance in ET began with a mean deviation of 7.2 cents and decreased to 4.5 cents in the last rendition, resulting in a mean deviation of only 1.9 cents in the fourth rendition. In the condition of J5, the performance of Player P decreased in accuracy, starting from a mean of 5.4 cents and ending with a mean of 8.8 cents. Already at this point, one can draw the initial conclusion that intonation is influenced by all variables of our investigation. As the interaction of tuning, rendition, interval category, and player shows, intonation is a dynamic process and is influenced by musical structure, task adaptation through repetition, and the player's expertise in different tuning contexts.

A THEORETICAL MODEL OF INTONATION: THE INFLUENCE OF HARMONIC FUNCTION, SPECIFIC PITCHES, AND THE INSTRUMENT'S IDIOSYNCRASIES

At this point, significant questions remain unanswered: What role does the underlying musical context (i.e., the accompaniment) play in an examination of intonation? Is intonation in different tuning systems determined by pitch invariance (see Figure 5) or by functional invariance (see Figure 6)? To answer these two questions, a principal component (factor) analysis (PCA) with Varimax rotation was conducted over the intonation of all pitches and intervals used in the experiment. The PCA resulted in a number of factor loadings that represent the correlations between the deviation and the factor score profiles. Factors with an "eigenvalue" larger than one were considered significant. A PCA will reveal only radically different intonation patterns and will disregard idiosyncratic intonation. If one rule is applicable to one intonation pattern in the five interval categories as well as the seven pitch classes, this would result in only one factor. The rotated PCA revealed four significant factors (see Table 3), resulting in an accumulated explanation of variance of 81% for all four factors together.

Factor I is the "major third factor" and can be explained by the intonation behavior that must be used for the performance of these intervals. The unadjusted partials of the trumpet that are used for major thirds are 13.7 cents lower than the pitch of an ET major third. This factor accounted for 24% of variance and represents—as a general tendency—an intonation

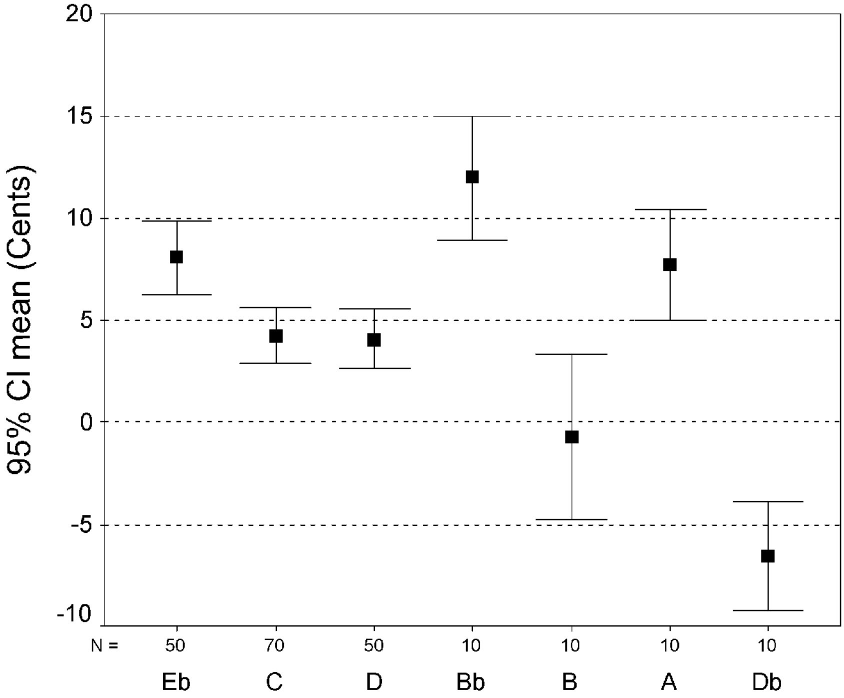

Fig. 5. Deviation of single pitches within the test composition in equal temperament for both subjects. N on the horizontal axis indicates the pooled number of performed pitches. Error bars indicate confidence interval (CI) of average intonation deviation.

pattern that determines the function of a major third and the three pitches D♭, A, and B. At first glance, it is unclear what connects the function of a major third and the three aforementioned pitches. A look at both subjects' protocols of valve combinations used for the performance of the test composition provide important clues: all pitches were generated by the use of standard valve combinations and without the use of special fingering. Fine tuning was done through the use of embouchure only. The two strongest factor loadings (the correlation between a factor score and a variable) for D♭ and B are related to pitches that were generated as major third partials. D♭ is performed by lowering the fundamental pitch to A with the second valve, blowing the D♭ as a C♯ partial. Similarly, B is obtained by lowering the fundamental pitch of the trumpet to G by use of the first and second valve and blowing the B as a fifth partial. The case of D♭ is of particular interest because its harmonic function in the test composition is that of a minor seventh (see Figure 6); however, the factor analysis shows no minor seventh pitch-related pattern of intonation with a separate factor for this harmonic function. This finding confirms our aforementioned assumption

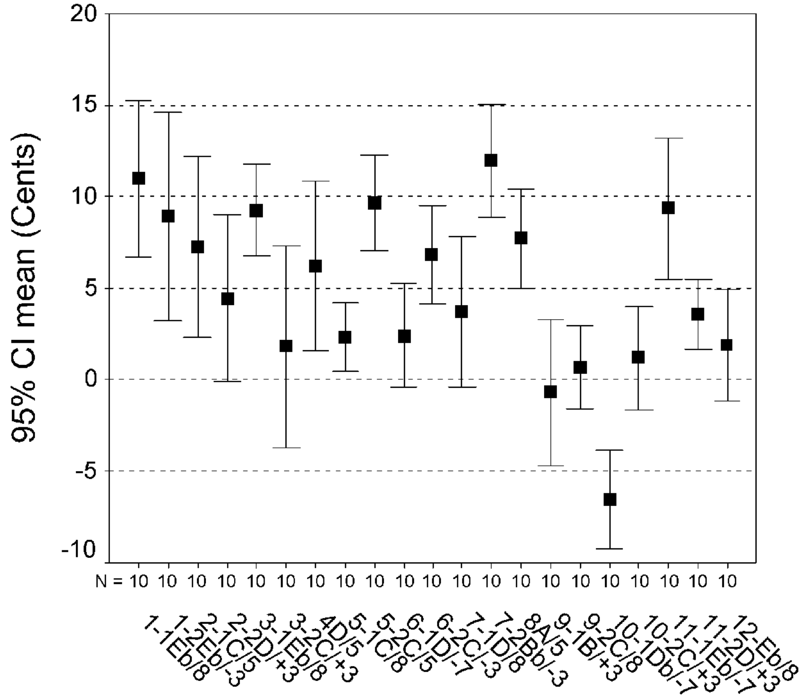

Fig. 6. Deviation of single pitches in equal temperament at different bar positions. Pitches are indicated with bar-beat/harmonic function. (8 = octave, -7 = minor seventh, 5 = fifth, +3 = major third, -3 = minor third.) N on the horizontal axis indicates the pooled number of performed pitches. Error bars indicate confidence interval (CI) of average intonation deviation.

TABLE 3
Rotated Factor Loadings of Pitches and Harmonic Functions for Deviations in Equal Temperament

Factor	I	II	III	IV
Octave				-0.702
Minor 7				0.852
Fifth				
Major 3	0.727	0.565		
Minor 3		0.877		
E♭			0.932	
C		-0.806		
D		0.900		
B♭			-0.753	
B	0.875			
A	0.715		-0.517	
D♭	0.927			

NOTE—Loadings smaller than 0.5 are omitted. For a description of factors, see text.

that the valveless production of a "natural" minor seventh (the seventh partial) is unusable for ensemble playing because of its strongly compressed pitch and its being produced by an altogether different playing technique.

Likewise, the pitch of an A has a high loading for Factor I and has the same attributes in the pattern of intonation represented by this factor. Contrary to other pitches with high loadings for this factor, the A does not serve as a major third but rather as a fifth. As Figure 6 shows, the A belongs to the upper end of highly tuned pitch classes and is only used once in the composition (bar 8). This pitch of an A corresponds to the previously mentioned tendency toward higher pitches in orchestras, and its production could be influenced by the kinesthetic memory of lip tension used for tuning to the commonly used orchestral pitch. This would be a context-free explanation. Alternatively, one could also interpret the intonation of an A from the perspective of harmonic structure: it is part of the closing chord of a cadence that resolves to G minor. In this case, the melodic movement from measures 7 to 8 would be B♭-A-B♭, with A functioning as a neighbor and leading note. This close proximity of a leading tone to its resolution is a common practice and a characteristic feature of most performances.

Factor II is called the "minor third and partials factor" because the highest loading values can be found in the interval function of a minor third and the pitches of C and D, and it accounts for 24% of variance. Negative factor loadings indicate the tendency to stretch intonation, whereas positive factor loadings tend to compress intonation. The harmonic function of a minor third in ET is characterized by a remarkable stretching of this interval, as can be seen in Figure 3. This intonation pattern can be explained partially by the nature of pitch production on the trumpet: unadjusted partials of the trumpet that are used as minor thirds are 15.6 cents higher than the pitch of an ET major third. Adaptation to ET intonation can be successful only if minor thirds are strongly compressed. This is managed by embouchure, such as in the adaptation of all partials to the system of ET. As the intonation deviation of major and minor thirds in Figure 3 shows, it seems to be easier to raise the pitch of a major third than to lower the pitch of a minor third. The result is a sufficient adaptation of major thirds to ET with an average deviation of less than 5 cents. Concerning the intonation pattern for the pitches C and D, both pitches are produced as major third partials but are used as minor thirds, major thirds, fifths, minor sevenths, and octaves in the context of the composition. This interaction between harmonic function and the acoustic features of a note might also be the reason for a further factor loading observed for the interval of the major third on Factor II.

Factor III is the "instrumental tuning factor" and accounts for 16% of variance. The most obvious feature of this factor is that the pitches of E♭ and B♭ have high loadings. As shown in Figure 5, E♭ and B♭ are also characterized by the largest amount of pitch increase. In Figure 6, these two pitches show the greatest pitch increase of all 21 melodic notes except for the last E♭ in measure 12, regardless of the pitches' harmonic functions. The previously mentioned high tuning of the trumpets, playing about 5–10 cents higher than the given sample tone at the beginning of the recording, corresponds to the increase in pitch during the performance of the test composition. This intonation pattern determines the pitch of B♭ as the fundamental of the trumpet played without valves as an octave partial and the pitch of E♭ as the tonic of the test composition, although the latter is produced as the third partial (= fifth) of A♭ (first valve).

Factor IV is the "octave-minor seventh factor" and accounts for 16% of variance. Only two intervals have high loadings for this factor: the octave and the minor seventh. The octave has the harmonic function as the fundamental of a chord, and the minor seventh represents the interval of most tension within a dominant seventh chord. Both intervals are played with a low deviation from ideal ET tuning (octave: mean = 4.8 cents, *SD* = 5.7 cents; minor seventh: mean = 1.7 cents, *SD* = 7.8 cents) and show a very stable intonation pattern, independent of their absolute pitch. Although three minor sevenths occur in the course of the test composition, D in measure 6-1 and E♭ in 11-1 (see also Figure 6), these two minor seventh show a different intonation pattern than D♭ in 10-1. This D♭ is the only seventh played with very compressed intonation (mean = -6.5 cents, *SD* = 3.7 cents). It seems to be an exception in the group of minor sevenths and, as mentioned earlier in the discussion of Factor I, D♭ has more similarities in its intonation pattern within the group of major thirds than that of minor sevenths, owing to its production as the major third partial of the fundamental pitch A.

Discussion

This study investigated the ability of two trumpet players to adapt to accompaniments tuned to either just intonation or equal temperament. The degree of adaptation was measured by analysis of the melody's deviation from expected pitches when assuming a perfect adaptation to each tuning system. A primary hypothesis was that the ability to play in tune and to adapt to a tuning system in a real-time situation is superior to—and displays less variability than—the intonation ability when only isolated intervals or pure tones are used.

DISSIMILARITIES TO FORMER STUDIES

Contrary to some previous studies that showed large zones of tolerance, we found that in situations of music making, the intonation ability is much better than the tolerance of 10–30 cents reported in earlier studies. One can assume that the entire information processing system of an expert performer will be activated to an optimal level if the task demands are set to a high level. Under this condition, the human information processing system will use all acoustical cues available, such as timbre, context, and beats to reach an optimal task adaptation. Unlike previous studies, the present experimental paradigm maintained a high degree of ecological validity. It is dynamic, that is, the performer receives task demands that change continuously throughout the experiment.

INTONATION PERFORMANCE AND LIMITATIONS OF CONTROLLABILITY

The crucial result of our study showed an overall deviation for intervals in ET and J5 that is much smaller than reported in previous studies. The adaptation to both systems was characterized by a mean deviation of less than 10 cents, but much smaller in ET than in J5. This means that intonation is controllable to a significant degree, despite a certain amount of indeterminacy that is characteristic for tone production under standard conditions. This "system noise" is caused by vibrato, pitch-dependent acoustic impedance of the instrument, and player fatigue. Therefore, the deviation for major thirds and minor sevenths of less than 5 cents can be interpreted as an exceptional achievement. Moreover, Meyer (1966) pointed out that a specific instrument's acoustical features could determine its intonation range (the so-called *Ziehbereich*). Within this range, the player can modify fundamental frequency by means of the embouchure. The range differs for instruments of the same type as well as between instruments of different groups of woodwinds. For example, in a mean register, the oboe has an intonation range between -5 and +60 cents, whereas the clarinet has a range between -10 and +50 cents (light read), respectively -5 to +60 cents (heavy reed). As a result, at least for woodwinds, we can conclude a remarkable range of available intonation. Informal measurements of our subjects revealed a total range of intonation on their own instruments of a half tone (100 cents), produced by embouchure.

GENERAL TENDENCIES IN INTONATION PERFORMANCE

The observed overall tendency of higher pitched intonation (see Figure 2) is an unexpected finding because the reference tuning pitch for the experiment had already been raised to A = 442.5 Hz; however, the subjects raised the pitch in the experiment even further to the region of 445 Hz. The null effect of nonsignificant differences between the deviations of performances in ET and J5 could at first be interpreted as successful task adaptation within the two tuning systems. However, an alternative explanation for this finding is provided with a simple transfer strategy, whereby the same intonation pattern for ET is used as for J5. As demonstrated in the analysis of the intonation for major and minor thirds, a simple transfer of the intonation of major thirds from ET to J5 produces exactly the observed amount of intonation bending (see Figure 3). Deviations of minor thirds in J5 can be similarly explained. Because of the significant interaction between the tuning system and interval category, one can hypothesize that this "always the same" transfer strategy is not deliberate but rather subconscious. This significant interaction can be interpreted as an unsuccessful trial of task adaptation.

EXPERTISE AND TASK ADAPTATION

Another noteworthy result was the excellent task adaptation for both players and for all intervals played under the condition of ET: all intervals ($n = 210$) were played with a mean deviation of less than 10 cents. This is a surprising result for "unnatural" intervals as found in ET (which are not beat-free and cannot be tuned by simple use of beats as acoustical cues). There were no significant differences for the players, the interaction between players and tuning system, or the interaction between players and interval category. Thus, one can assume that this ability to adapt to an ET system must have been acquired already within the first 10 years of playing the trumpet. The semiprofessional player (Subject S) already exhibited signs of ability to adapt to ET at a higher level than expected. To understand the complex demands of trumpet playing, one must remember that the fundamental frequencies of a trumpet depend on the resonance frequencies of the instrument, which are not strictly tuned to just intonation, and which have to be adjusted to J5—as well as to ET—interval sizes through the use of the embouchure.[5] However, there is no current theoretical explanation for how this task adaptation works under the constraints of real time. As neither subject possessed perfect pitch, it cannot be assumed that pitch has been stored in the memory as a kind of absolute value. One can only as-

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[5] However, we have to bear in mind that the effect of a discrepancy between partials and the instrument's resonance curve is weak. As Benade (1973, 1976) showed, because of the shape of the trumpet's horn, the fundamental frequencies can differ from just intonation. This effect is most relevant for the very low register between $B\flat_2$ and $B\flat_3$ and the deviation from just intonation disappears with increasing fundamental frequency. Although the lowest pitch used in our test composition was a sounding G_4 and the intonational shift is expected to be very small, the problem shall be mentioned here to complete the picture. In another investigation, Backus (1976) analyzed the differences between the resonance curve of a trumpet and the frequencies of its partials. He showed that the aim of instrument building, namely to reduce these discrepancies to close to zero in properly designed bell and mouthpiece, can be accomplished in high-quality modern instruments. Additional means, such as slides on the third valve, realize this goal also in modern valve instruments.

sume that the subjects rely on acoustical cues (e.g., roughness of sound) and kinesthetic experiences such as the specific lip muscle tension. This process of stepwise adaptation (which always uses an external calibration system, such as an equal tempered piano already in the early phase of instrumental lessons) causes a kind of "burn-in effect" and is related to the establishment of intonation patterns.

Because most trumpet performances take place with equal tempered instruments such as the piano, it is not surprising that the expertise in the domain of ET intonation is developed to an exceptionally high degree. One can confirm the predictions of expertise theory, namely, that expertise is always domain-specific (Ericsson, 1996) and needs sufficient time for skill acquisition. Already Moran and Pratt (1928) observed that musically trained subjects can adjust the frequencies of two oscillators to given harmonic intervals significantly better in ET than in J5.

In general, one can assume that the player's adaptation to J5 would be superior, for instance, after a longer period of intense rehearsing (i.e., in a brass ensemble). For example, Sundberg (1987, p. 178) showed that barbershop singers can adapt to beat-free just intonation with a mean deviation of less than 3 cents. The results of this study are also congruent with the intonation tendencies observed in Karrick's (1998) investigation. The deviation of wind players was less for ET (mean = 6.5 cents) than for Pythagorean (mean = 8.7 cents) and J5 (mean = 13.1 cents) versions. However, although the same tendency was observed in our study, the deviations were much smaller (mean for ET = 4.9 cents; mean for J5 = 6.7 cents). Finally, I agree with Fyk (1995) that intonation is a dynamic process affected by many influences, but I maintain that this process is characterized by a much higher degree of control than observed to date.

SPECTRAL CUES

Another critical point in the successful task adaptation could be the influence of headphones used in the experiment for the playback of the accompaniment. The direct transmission of the accompaniment to the external auditory canal could have influenced the accompaniment's timbre by increasing the higher partials' amplitude, resulting in additional spectral cues for intonation. As Meyer (1978) showed, perceived differences in pitch can be influenced by changes in timbre. Musicians perceived smaller pitch differences if their own instrument's or a related timbre was used rather than sounds with incomplete spectra. However, the observed effect was very small (>20% of the musicians could discriminate pitch changes of 2 cents in sinusoids that have no spectral information), and no statistics are indicated. Whether this effect brought about by the use of headphones is relevant to our experiment is uncertain because the experimental condition of Meyer was very restrictive (subjects listened to the samples repeatedly, and only stationary sounds without vibrato were used) and cannot be compared with our real-time condition. Experimental verification of the timbre's potential influence could be tested only by use of a low-pass-filtered accompaniment.

Concerning the method of intonation analysis, only the frequencies of the interval between bass and melody note were included in the analysis. Another interesting aspect of analysis would be the question of whether the accompaniment's spectrum could encourage the perception of the underlying intonation system by offering prominent spectral "peaks" that could serve as additional acoustical cues for intonation. However, such an analysis would only make sense if psychoacoustic methods of analysis (so-called auditory spectrograms that take such factors as masking effects into consideration) are used instead of simple methods based on fast Fourier transforms. This analysis would require very sophisticated procedures.

THE INFLUENCE OF BEATS AND JITTER

Regarding the use of slow beats as a cue for intonation, two points must be considered: (a) a natural variation in frequency of all wind and brass instruments can superimpose the perception of beats, and (b) slow beats depend on the note's frequency and require a minimum length. Although note length was sufficient for analysis (the quasi-stationary part had a length of 1.5 s), the question of fluctuations in frequency remains open. Players were instructed to avoid the use of vibrato, and the accompaniment used vibrato-free sounds. It is not clear whether or not the condition of vibrato-free sounds for the formation of relatively slow beats was fulfilled. To test our assumption of quasi-stationary trumpet pitches, an analysis of jitter (the relative average perturbation) was processed, using the software Praat (Boersma, 2000; Version 3.8.16), for 1.5-s-long sections of the quasi-stationary part of all 21 melody notes of the best and worst J5 performances. Jitter analyses revealed a mean value of 0.6% jitter for the worst and 0.2% for the best J5 performance. Compared with the amount of jitter of the open strings of a viola (mean jitter: 0.1%) and of a violoncello (mean jitter: 0.3%), jitter in trumpet tones was very low; thus, we can conclude that the best J5 trumpet performance reached a jitter level comparable to the jitter levels of the open strings of string instruments. Beats between accompaniment and solo voice can be used as a bottom-up cue for intonation, and beats remain nearly uninfluenced by vibrato.

However, whether beats between fundamental frequencies and melody notes, or between partials and melody notes, produce the strongest acoustical cues for intonation remains inconclusive. Selective spectral analysis of the first two note events and the accompanying chords showed a complex relationship between the spectrum of the accompaniment and the sounding melody note: the first melody note should have a frequency of 626 Hz, both in ET and J5. It coincides perfectly with the sixth partial of the accompaniment (the accompaniment's spectrum includes about 20 partials in a frequency range of 3.0 kHz). In this case, beats between the accompaniment's sixth partial and the melody note might have been used for orientation. In the second chord, we have a different situation: the melody note should have a frequency of 626 Hz (in ET) and of 632 Hz (in J5). However, no partial of the accompaniment coincides with either one of these melody frequencies; only the accompaniment's fifth partial has a frequency (655 Hz) situated within the frequency vicinity of the second melody note. Thus, in this second case, slow beats resulting from the deviation of nearly coinciding frequencies in solo voice and accompaniment cannot be used for intonation adaptation. One might conclude that beat rates are only one acoustical cue in the successful adaptation to different tuning systems.

INTERACTION BETWEEN MELODIC AND HARMONIC INTONATION

An important point for the discussion of results is the potential influence of melodic intonation. Of course, we intended to minimize the degree to which the harmonic intonation can be overrun by expressive melodic intonation. The fact that only harmonic intonation was measured may limit the range of our results. However, despite the "neutralized" and relatively inexpressive melody of the test composition, an influence of subconscious expressive deviations in performance cannot be completely excluded. The material offers interesting perspectives for future analysis of the interaction between harmonic and melodic intonation.

STRATEGIES OF INTONATION AND PERCEPTUAL PROCESSES

From these results, one must ask which strategies are used by the subject to adjust intonation within different contexts. For example, as Burns and Ward (1978) showed, boundaries of categorical perception for stretched or compressed intervals can be as high as 50 cents. This finding is supported by Hall and Hess (1984), who investigated the acceptance of an interval as representative of the specific interval, finding that major sixths could be stretched by a remarkable amount of about 80 cents until the interval was judged as a minor seventh. Very small mistunings for the octave were easily perceived, but this proved more difficult for thirds and sixths. One can also conclude from their results that beat rates are not the only information used to adjust intonation. When analyzing the perceptual strategies of their subjects, the authors concluded that "the less beat-dependent a subject's strategy, the greater the success the subject had with the binaural task" (p.

189). Nevertheless, we cannot be completely sure why subjects tend to play closer to ET than J5. Embouchure, experience with pianos, and a general tendency toward equal-sized pitch categories might be of relevance. One phenomenon is that both subjects could successfully discriminate in the informal aural test between computer-generated intonations, but not between intonations in their adaptation. Perception and performance of intonation do not seem to be congruent. An obvious difference between both activities is the more active role in performance. Skills demonstrated in isolated intonation tasks differ from a performance within a complex musical setting. Thus Morrison and Fyk (2002) assume "intonation is an amalgam of several subskills including pitch discrimination, pitch matching and instrument tuning" (p. 183).

The assumption of a high degree of determinacy of intonation methods brings the question of the perceptual mechanism of intonation into focus. While playing in an ensemble, the performer has to cope with a twofold task: the solo voice and the accompanying context must be processed simultaneously. However, chords should not be viewed as local frames where the hierarchy determines the intonation of a melody note. This view of intonation would be inadequate because the melodic line of an accompanied solo instrument always underlies expressive deviations in intonation, timing, and dynamics. Based on the study by Povel and Egmond (1993), who found that melody and accompaniment are processed relatively independently and are thus determined by a less hierarchical mechanism of music perception, it is proposed that a certain degree of dependence of the melody on the harmonic progression is necessary for successful intonation adaptation. This would result in a nonhierarchical yet interconnected perceptual relationship between melody and harmony.

Summary and Conclusion

A number of summarizing statements can be made. First, harking back to the research questions stated at the beginning of this article, we can now conclude that professional musicians are indeed able to adapt to ET but cannot discriminate in their performance between two tuning systems such as ET and J5. Second, intonation did not improve with repeated execution of the experimental composition. Third, individual players did not differ in terms of sensitivity to different degrees of mistuning. Additionally, no differences in performance could be found between the professional and the semiprofessional trumpeter. Finally, no evidence for Fyk's (1995) hypothesis of "tonal gravity" could be found, namely, that intonation is ruled by a simple mechanism, where intervals closer to the tonic show less intonation deviation than intervals farther away from the tonic. This assumption may be overly simplistic, and we argue that intonation is a complex process influenced by both bottom-up and top-down factors. For example, the slow tempo of our test composition encourages tuning by minimizing the effect of beating as a bottom-up strategy of intonation; however, contextual knowledge of a note's harmonic function in a sounding chord determines the performer's intonation strategy. Consistent with the study of key in tone profiles (Parncutt & Bregman, 2000), we conclude that a fundamental characteristic of perception is the real-time interaction of both processes.

The factor analysis (see Table 3) confirms this view, showing that intonation is influenced by at least four factors: instrument-specific effects, effects of partial position on pitch production, musical context, and pitch classes independent from the context. For example, in Figure 6, the resolution of the major third D in measure 2-2 to the tonic E♭ in 3-1 is characterized by a greater deviation than the resolution of the same interval (but with a different pitch to a different tonic; c minor) within measure 9. There are contrasting views concerning the role of musical context in the amount of intonation deviation. Burns (1999, p. 235) claims that "the accuracy of identification and discrimination does not appear to be markedly different in context or in isolation," and Gabrielsson (1999, p. 546) pronounces "the importance of the melodic and harmonic context." This contradiction can be resolved: if the potential influence of musical context is reduced by the use of a bottom-up paradigm, then context effects, as included in a top-down approach, cannot occur.

These results open up new perspectives for music education; for example, the surprisingly successful adaptation to the "unnatural" ET system shows that deliberate practice is required to obtain task adaptation. As Kantorski (1986, 1997) describes, modern computer systems could deliver valuable support to improve violin intonation. Although music theorists such as Vogel (1961) are occasionally convinced of just intonation in real music making, it is not possible to support his assumption "on brass instruments . . . equal tempered intonation is unattainable" (p. 97). This idea underestimates the importance of musical context and the human factor: it is not the trumpet, but (predominantly) the trumpeter who creates the music.[6]

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