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Some observations on operatic singer's intonation

ABSTRACT: Fundamental frequency (F0) patterns are analysed in six recordings of the *Romance* from the First Act of Guiseppe Verdi's opera *Aida*. Two of the recordings were sung by the late Swedish tenor Jussi Björling and the remaining four by other international premiere tenors. F0 tracking was carried out semi-automatically using the autocorrelation program of the Soundswell Signal Workstation™ software. Intonation characteristics were measured in relation to equally tempered tuning (ETT) based on the tuning of the orchestra. Great individual differences are found. The mean deviation from ETT varied between – 15 cent and + 30 cent. Only Björling tended to increasingly sharpen intonation, the higher he sang in his passagio region. Moreover, in the long sustained high note at the end of the Recitative he added a *Portamento* at the end, while the other singers increased F0 by about 40 cent over the same tone. Vibrato rate and extent were similar among the singers, but spectrum analysis of the vibrato waveform revealed various differences. The final descending octave interval exceeded the 2:1 frequency ratio in all singers except one. The results are discussed from the points of view of interval perception, performance practise and musical expression.

KEYWORDS: singing, intonation, octave, Jussi Björling, vibrato

Introduction

Pitch constitutes the material out of which melodic and harmonic patterns are built in music. As a consequence, it has attracted much research interest in the area of music theory. This research has mostly focused on what is written in the score.

During the last decades, however, also music performance has gained a strong interest in music science. This research has revealed that performing musicians make substantial departures from what is nominally written in the score. The deviations concern not only the duration and timing of the tones, but also, in cases of instruments with freely adjustable intonation, their fundamental frequency F0. This suggests that musicians take advantage of intonation as an expressive tool.

Reviews of the research on intonation in music performance can be found elsewhere.[1] The results have shown that some of the deviations that musicians make in their performances from the equally tempered tuning (henceforth ETT) are systematic.

The principles underlying such systematic deviations were studied by Rakowski.[2] He had highly skilled musician subjects adjust different within-octave intervals, using a 500 Hz tone as the lower, reference pitch. The signals used had sinusoidal, triangular or squared waveforms. The subjects' tunings were similar for the different stimulus waveforms and matched neither equally tempered, nor Just, nor Pythagorean tuning. Rather, narrow intervals were compressed while intervals wider than a fifth were stretched. Moreover, he noted similar intonation trends when musicians were asked to play musical intervals in various melodical contexts.

Sundberg and associates[3] had an expert panel mark all tones perceived as out of tune in 10 recordings of Franz Schubert's *Ave Maria*. They then analysed mean F0 of tones which no panel member complained about and of tones which nearly all panel members complained about. The results were rather surprising. Tones with an average F0 exactly matching ETT were perceived as in tune in some cases and out of tune in other cases. They also found that in most cases the mean F0 values of tones perceived as in tune were scattered within a range of about ±10 cents, while tones with a mean F0 outside this range tended to be perceived as out of tune. Thus, the tolerance zone appeared to be on the order of ±10 cents. However, for some tones the tolerance zone was much wider. This suggested that what is perceived as in tune may be quite dependent on musical and/or performance contexts. Another observation was that there seemed to be a greater tolerance for sharp than for flat intonation of tones, an observation in accordance with the results reported by Rakowski.[4]

Vurma and Ross[5] measured the accuracy of thirteen subjects educated as singers at the Estonian Academy of Music for at least 4 years. The subjects repeatedly performed ascending and descending minor seconds, tritones and

[1] Edward M. Burns, 'Intervals, Scales and Tuning', in *The Psychology of Music*, ed. Diana Deutsch (San Diego, 1999), 215-264; Alf Gabrielsson, 'The Performance of Music', in *The Psychology of Music*, ed. Diana Deutsch (San Diego, 1999), 502-602.

[2] Andrzej Rakowski, 'Intonation Variants of Musical Intervals in Isolation and in Musical Contexts', *Psychology of Music* 18 (1990), 60-72.

[3] Johan Sundberg, Eric Prame and Jenny Iwarsson, 'Replicability and accuracy of pitch patterns in professional singers', Chapter 20 in *Vocal Fold Physiology, Controlling Complexity and Chaos*, eds. Pamela Davis and Neville Fletcher (San Diego, 1996), 291-306.

[4] Rakowski, 'Intonation variants'.

[5] Allan Vurma and Jaan Ross, 'Production and Perception of Musical Intervals', *Music Perception* 23 (2006), 331-344.

fifths. The results showed that, averaged across subjects, the intervals deviated from their equivalents in the ETT by -17 to +125 cents, the fifth showing the greatest deviations. The mean standard deviation was 34 cents. They also had a listening panel assess the tuning of the singers' intervals and noted that samples with a large standard deviation of F0 were perceived as out of tune more frequently than other intervals, and that the intervals could deviate form their target size by about 20 cents without being perceived as out of tune.

Rapoport[6] analyzed F0 contours of individual tones in sung performances. He grouped the patterns observed in terms of a system of 'singing mode categories': 'Neutral/Soft', 'Calm', 'Expressive', 'Transitional/Multistage', 'Intermediate', 'Short', 'Excited', 'Virtuoso'. He used this system to describe, classify and interpret the expressive deviations of famous singers' performances of examples from the opera and Lied repertoires.

The aim of the present investigation was to analyse in some detail intonation in sung performances of a piece of music taken from the opera repertoire. More specifically, the intonation measured in two recordings of the late Swedish tenor Jussi Björling are compared with four other internationally renowned tenors' renderings of the same piece.

Method

Radames' *Recitativo* preceding the *Romanze* in the first act of Verdi's opera *Aida* was selected for analysis, see Figure 1. This excerpt had the advantage of presenting several samples of unaccompanied singing, which facilitated F0 tracking. Two recordings of Jussi Björling were analyzed, one apparently recorded live during an opera performance and one from a studio recording. In addition, for reasons of comparison, also recordings of four other singers were analyzed: Carlo Bergonzi, Placido Domingo, Luciano Pavarotti, and Richard Tucker.

[6] Eliezer Rapoport, 'Emotional Expression Code in Opera and Lied Singing', *Journal of New Music Research* 25 (1996), 109-149.

Figure 1. Score of the Recitativo.

The recordings were taken from CD records or from Youtube on the Internet. They were transferred to the .smp signal file format by means of the Soundswell signal workstation. Figure 2 shows an example.

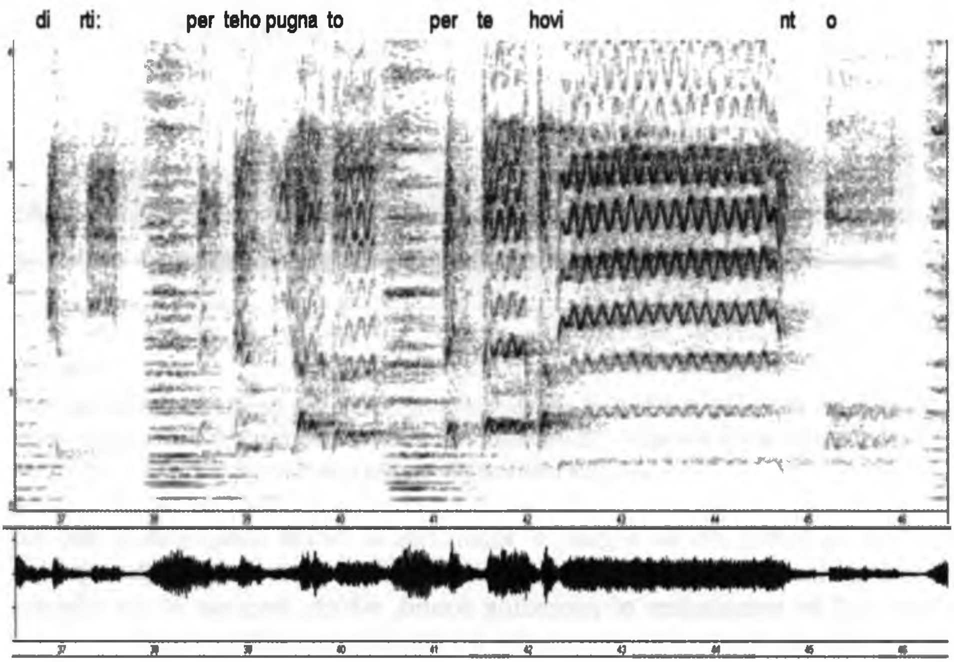

Figure 2. Spectrogram and audio signal of the last phrase of the Recitativo.

F0 tracking was carried out semi-manually by means of the Corr program in Soundswell Signal Workstation™ software. Figure 3 illustrates how this program works.[7] It produces a correlogram, which shows, along a gray-scale, the correlation between time windows of varied widths containing adjacent sections of the input signal. The correlogram ordinate represents the inverted window width, i.e., frequency. When the window contains exactly one single period, correlation becomes high. Hence the fundamental frequency is shown as a black trace in the correlogram. However, also when the window contains two or more complete periods, correlation becomes high. Therefore also F0/n, n=1, 2, 3.. tend to produce black traces. The operator marks the correct F0 values by means of fence lines, and the program discards all frequencies outside these fences. The figure also shows the resulting F0 trace.

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7 Svante Granqvist and Britta Hammarberg, 'The Correlogram: a Visual Display of Periodicity', *Journal of the Acoustical Society of America* 114 (2003), 2934-2945.

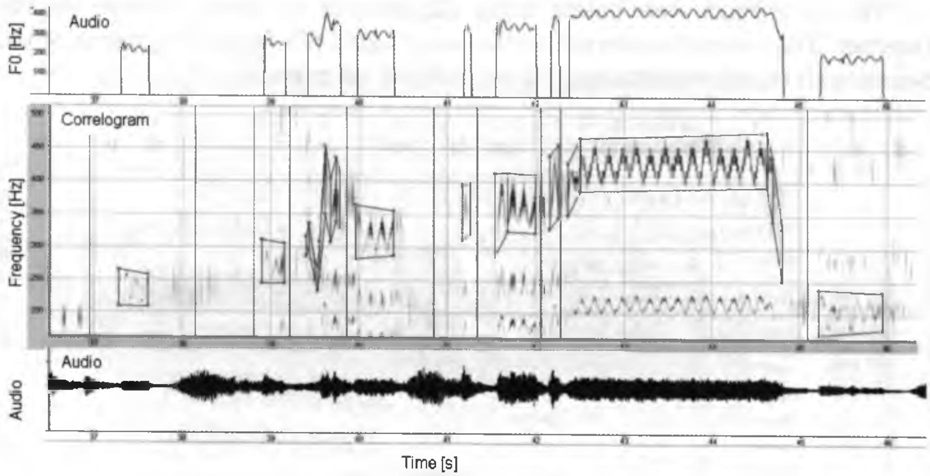

Figure 3. Audio signal, correlogram and the resulting Fo data for Bergonzi's performance of the last phrase of the Recitativo. The straight line fences, set manually in the correlogram, shows the limits of allowed Fo values.

The spectrogram in Figure 2 illustrates a factor complicating the Fo tracking, namely reverberation. It implies that the periodicity of the signal is disturbed by remainders of preceding sound, which, because of the vibrato, has a different Fo. For this reason, the Fo tracking sometimes failed.

Since the pitch perceived of a vibrato tone corresponds almost exactly to the frequency averaged over a vibrato period[8] the mean Fo values of the tones were measured by means of the histogram program of the Soundswell system. Thereby care was taken to select for measurement a set of complete vibrato periods.

The Fo averages were then converted to the logarithmic semitone unit using the equation

$$I = 39.86 * \log_{10} (Fo/Fo_{Ref})$$

where Fo_{Ref} is the Fo of the pitch of A4 reference. This Fo value differed between the recordings. It was measured from sustained single orchestral tones, such as those found in bars 12 and 25. From this value the tuning of A4 was calculated. Results are given in Table 1.

[8] Johan Sundberg, 'Effects of the Vibrato and the 'Singing Formant' on Pitch', in *Musica Slovaca* VI (Bratislava, 1978), 51-69; also in *Journal Research in Singing* 5/2, 5-17; John I. Shonle and Kathryn E. Horan, 'The Pitch of Vibrato Tones', *Journal of the Acoustical Society of America* 67 (1980), 246-252; Rachel M. van Besouw, Jude S. Brereton and David M. Howard, 'Range of Tuning for Tones with and without Vibrato' *Music Perception* 26 (2008), 145-156.

Table 1. Frequencies of A4 used in the recordings as calculated from sustained single tones played by the orchestra.

Jussi Björling live recording	446 Hz
Jussi Björling studio recording	440 Hz
Carlo Bergonzi	445 Hz
Placido Domingo	444 Hz
Luciano Pavarotti	440 Hz
Richard Tucker	444 Hz

Given these tuning references, the mean F0 values could be expressed in semitones relative to the accompaniment tuning.

Results

Figure 4 shows the singers' deviations, averaged across all measured tones, from ETT related to the respective orchestral reference. Björling showed rather small mean deviations, 4 cent and -15 cent for the two recordings analysed. This is quite small as compared with Bergonzi, Domingo and Pavarotti. It should be kept in mind, though, that these values are quite dependent upon how accurately the orchestra adhered to their tuning reference. It is well known that a rise of the ambient temperature will significantly raise the tuning of wind instruments.

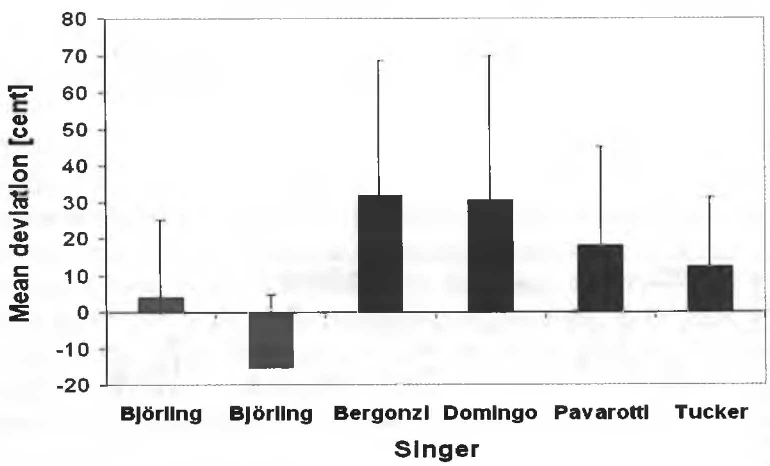

Figure 4. Average deviation from the equally tempered tuning adjusted to orchestral reference.

Figure 5 shows as function of pitch Björling's intonation in terms of the deviations from ETT. In the live recording the deviations are quite close to zero up to the pitch of D#4, i.e. 6 semitones below A4. This pitch D#4 corresponds to the lower limit of most tenors' *passagio* region. A trendline indicated that the average rise in this top range amounted to 7.9 cent / semitone (r =.625). A similar, though weaker trend can be discerned in the same range in the studio recording (trendline slope 6.8 cent / semitone, r = 0.410). Figure 6 shows the corresponding data for the remaining singers. No similar pattern can be seen in any of the four singers, thus suggesting that the increasing sharpening of tones with increasing pitch in the *passagio* range may be a characteristic of Jussi Björling's vocal art.

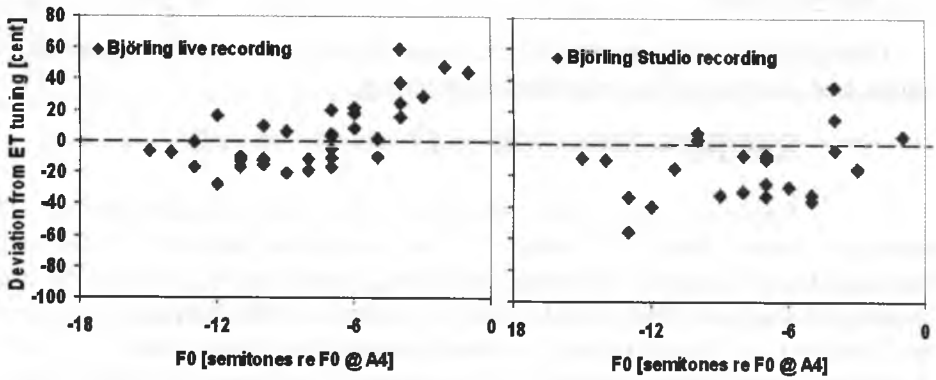

Figure 5. Jussi Björling's' deviations from equally tempered tuning in the indicated recordings relative to the orchestra's tuning of the pitch of A4.

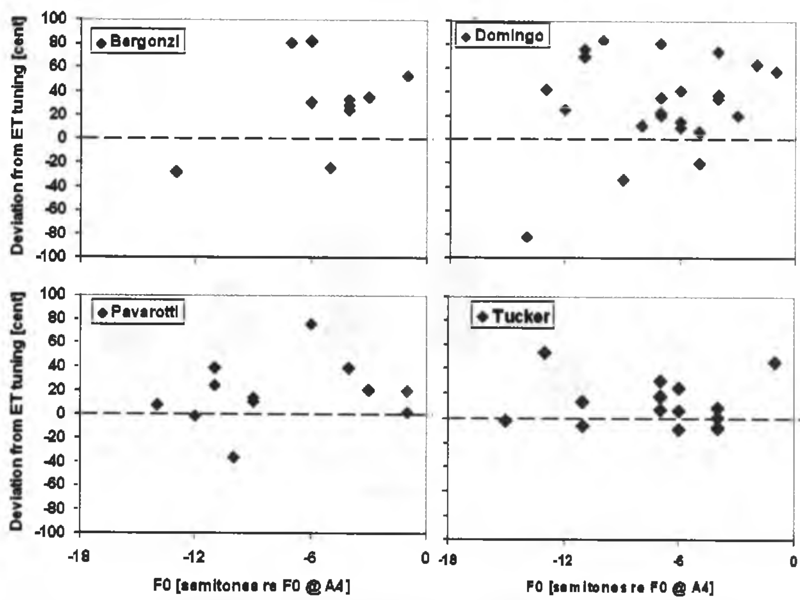

Figure 6. The indicated singers' deviations from equally tempered tuning, relative to the orchestra's tuning of the pitch of A4.

Of particular interest is the intonation of the final descending octave interval from Ab4 to Ab3. An octave interval tends to be perceived as being too narrow when corresponding to the 2:1 frequency ratio.[9] In addition, Björling was found to stretch this interval considerably in a previous study.[10] Figure 7 compares the different singers' size of this interval. All singers except Tucker stretched the interval, Bergonzi by no less than 81 cent. Thus, he sang it just 19 cents narrower than a minor ninth interval. The stretch of the two versions of Björling's octave was close to 40 cent, while Domingo and Pavarotti were both less than 20 cent.

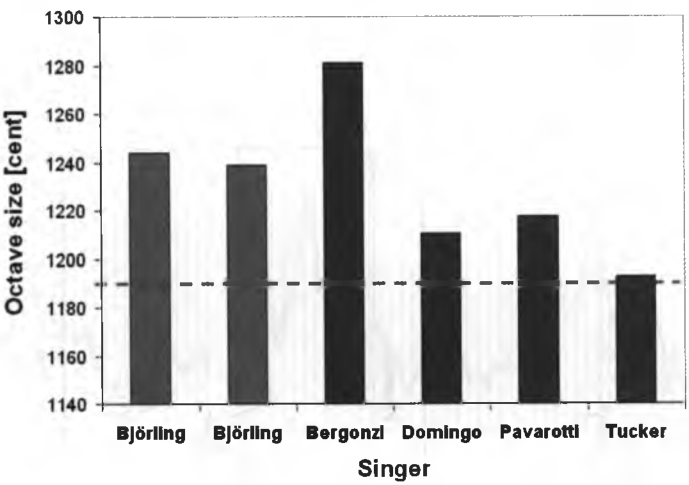

Figure 7. The indicated singers' sizes of the final descending octave interval in the recitivo.

The vibrato rate and extent was measured in the upper tone of the final descending octave. F0 averaged across every half vibrato period is shown for this tone in Figure 8. The data have been normalized with respect to the mean F0 of the tone, thus disregarding the tuning of this tone. Only Björling made a *portamento* towards the following Ab3. Bergonzi, and Pavarotti, by contrast, made a quick glissando in the beginning of the tone, both starting about 35 cent below the mean F0, reaching the target F0 after two vibrato periods. Domingo and Tucker also started the tone around 20 cent below the target but continuously increased F0 throughout the tone, ending about 10 cent above the average F0.

9 Johan Sundberg and Jan Lindqvist-Gauffin, 'Musical Octaves and Pitch'. *Journal of the Acoustical Society of America* 54 (1973), 922-929.

10 Johan Sundberg, 'On the Expressive Code in Music Performance', in *Festschrift Franz Födermayr zum 75. Geburtstag,* ed. August Schmidhofer (Tutzing, in print).

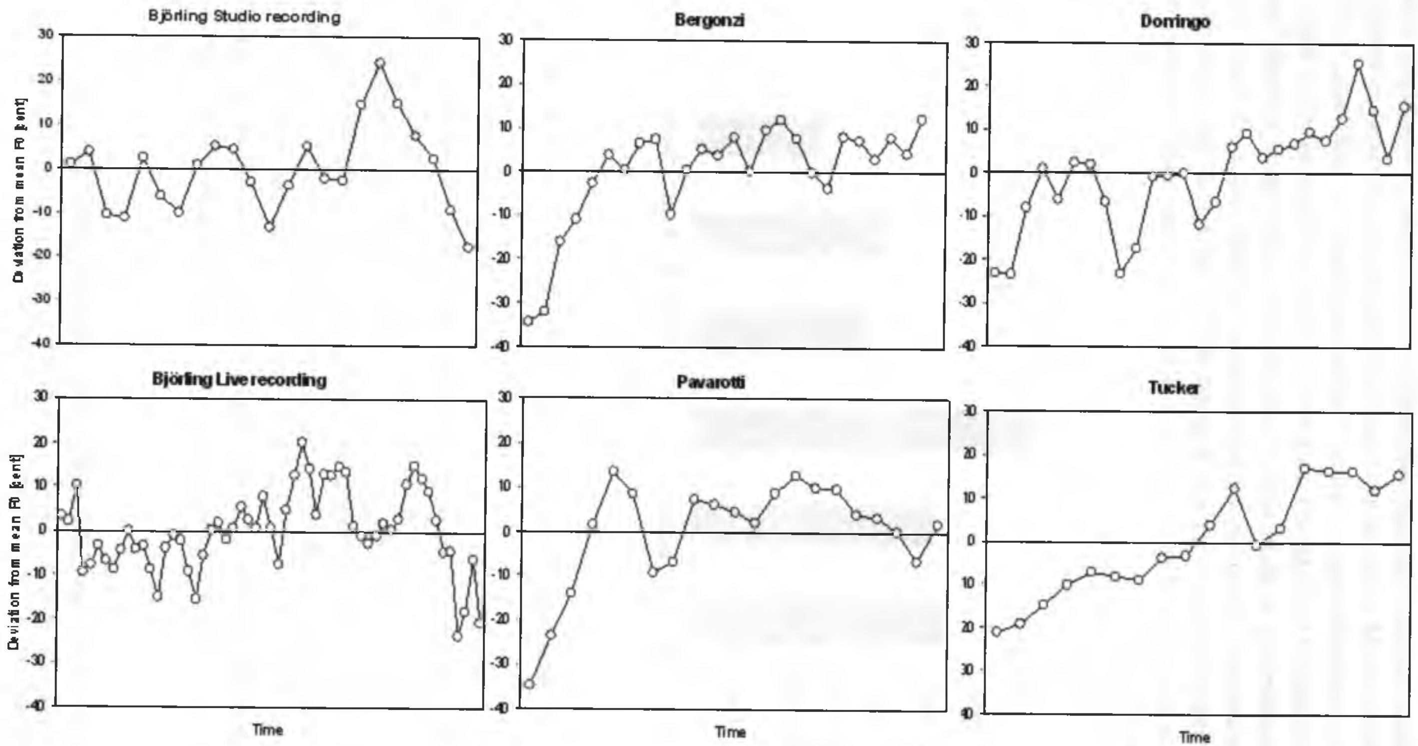

Figure 8. The indicated singers' deviations from their F0 average of the sustained tone in bar 21. Each data point corresponds to the mean of half a vibrato cycle measured at its peak and valley.

Results regarding vibrato rate and extent are listed in Table 2. The rate was somewhat faster in Björling's studio recording than in his live recording. For all singers it was close to 6.5 Hz, except for Domingo who had 5.5 Hz. The peak-to-peak extent was close to 125 cent for Björling's two recordings and near 160 cent for the other singers except Tucker, who had an extent similar to Björling's.

The vibrato waveform is generally quite close to sinusoidal in the singers, as illustrated in Figure 9, which shows spectrum analysis of the vibrato in the same Ab4 tone in the final phrase. Weak periodicity can be found at three times the vibrato rate and in Pavarotti's voice also at twice that frequency. It should be kept in mind, though, that deviations from a perfectly periodic vibrato will hide other periodicities in these analyses.

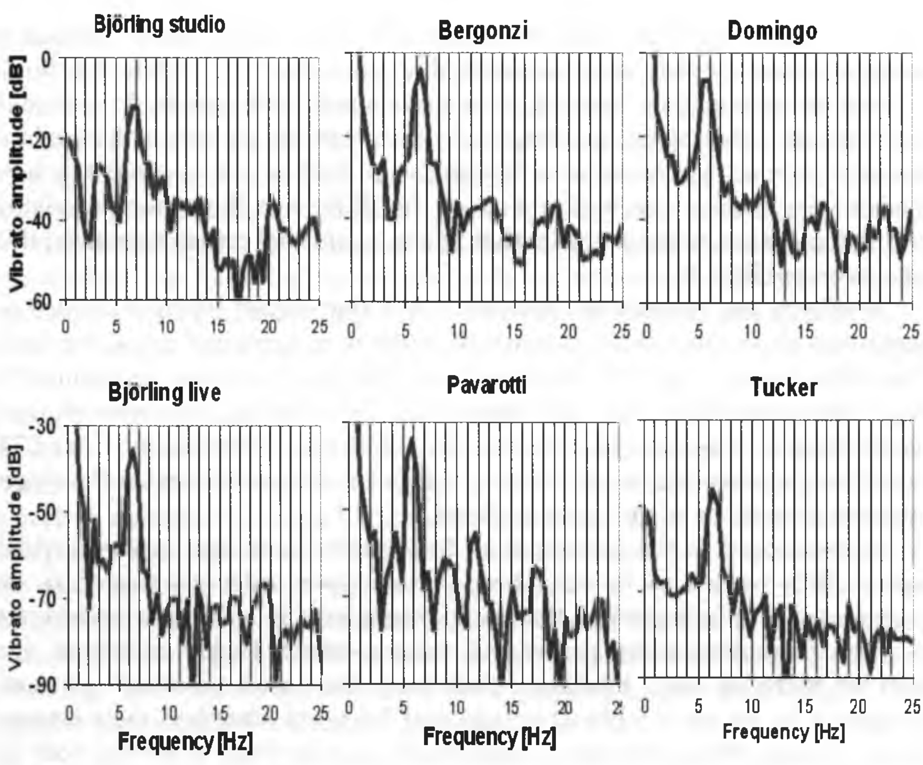

Figure 9. Spectrum analyses of the indicated singers' vibrato waveform in the sustained tone in bar 21.

Table 2. Vibrato rate and peak-to-peak (ptp) extent as measured for the pitch of Ab4 of the final descending octave.

	Mean rate	SD	Mean extent	SD
	Hz	Hz	ptp cent	cent
Björling studio	6.9	0.4	123,0	16
Björling live	6.2	0.4	129,0	18
Bergonzi	6.3	0.4	154.0	18
Domingo	5.5	0.5	161,0	20
Pavarotti	6.2	0.3	160,0	13
Tucker	6.6	0.1	132,0	12

Discussion and conclusions

Our analyses have demonstrated that international premiere operatic tenors deviate quite considerably from the ETT. While Björling's average deviations, like Tucker's, were quite small, with standard deviations near 20 cent, Domingo's and Bergonzi's were close to 30 cent with standard deviations about twice as large as Björling's and Tucker's. It is relevant to view these values against the background of the difference limen for perceiving intonation errors. As far as this author knows, no formal measurements of this have been published.

Sundberg and associates[11] however noted that expert listeners tended to agree that tones more than 10 cents off target were perceived as out-of-tune. This indicates that at least Domingo's and Bergonzi's deviations from ETT would be perceptible. On the other hand, considering the international recognition of these singers, it seems obvious that their deviations from ETT would not be perceived as out of tune. This poses the question what the target intonation would be of the tones analysed.

As mentioned in the Introduction, Rakowski[12] found that intervals wider than a fifth tended to be stretched and narrower intervals tended to be compressed. The only interval that could be analysed in all singers' recordings was the final descending octave. All tenors except Tucker stretched this interval more or less. Björling's stretching amounted to about 40 cent, Bergonzi's to 80 cents while Domingo and Pavarotti stretched their octaves about 15 cent. These stretches substantially exceed those observed both in adjustment experiments and in measurements of performances.[13]

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[11] Sundberg, Prame and Iwarsson, 'Replicability and Accuracy'.

[12] Rakowski, 'Intonation Variants'.

[13] Rakowski, 'Intonation Variants'; Janina Fyk, *Melodic Intonation, Psychoacoustics and the Violin* (Zielona Góra, 1995); Johan Sundberg and Jan Lindqvist-Gauffin, 'Musical Octaves'.

Björling was the only singer who showed a tendency to increasingly sharpen pitches in the passagio region (i.e. above D4) with rising pitch, as was illustrated in Figure 5. At the top pitch the sharpening was about 40 cent. The "High-Sharp" rule in the Director Musices performance grammar, which was derived by analysis-by-synthesis of instrumental music performance, produces a similar effect, even though it amounts to no more that a few cent per octave.[14] Many musicians are well aware of this tendency to play high tone sharp, sometimes colloquially expressed in terms of the aphorism 'Better be sharp than out of tune'.

Summarising it is clear that these singers' intonation deviated much more from ETT than what has been observed in listening experiments and in analyses of instrument performances. A performance characteristic of operatic singing likely to allow such great tuning modifications would be the vibrato. Since it is produced by a quasi-periodic modulation of F0, off-pitch intonation of tones will not generate beats with accompaniment instruments. Hence the vibrato eliminates the risk of beats. It may be relevant that for the top tone sustained on the pitch of Ab4 in bar 21, the singers had a vibrato extent that was close to ± 60 or 70 cent. This is much wider than what is used in instrumental performances.

The FO curves for this high tone Ab4 differed considerably between the singers. The excursions from a constant F0 throughout the tone clearly exceeded the subliminal threshold. Here Björling used a strategy differing from that used by the other singers. He stayed close to a constant mean F0 but approached the following lower note with a *portamento*. The other singers started the tone flat and sharpened it successively, thus producing an overall sharpening over the entire tone that amounted to about 40 cent. It seems safe to assume that FO curves such as a *portamento* or a constant increase of F0 over a long tone carry some sort of expressive meaning. Some decades ago Makeig and Balzano[15] reported that listeners perceived differing affective colours when listening to octave intervals of different sizes. For instance, some listeners perceived a stretched octave as affirmative and secure, while a compressed octave was perceived as insecure. Indeed, such meanings of pitch patterns may be one of the most essential elements in music experience. Yet, they probably cannot be exhaustively described in verbal terms. On the other hand, with today's studio recording technology it would be possible to manipulate such pitch patterns in recordings and explore the effects on the expressive colours scientifically. That seems a most attractive avenue for future studies of intonation.

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[14] Anders Friberg, 'A Quantitative Rule System for Musical Expression', PhD thesis, KTH (Royal Institute of Technology – Sweden, 1995), also available online at http://www.speech.kth.se/music/publications/thesisaf/sammfa2nd.htm, ccessed November 2011.

[15] Scott Makeig and Gerald Balzano, 'Octave Tuning – Two Modes of Perception', *Proceedings of the Fifth Symposium on the Acoustics and Psychoacoustics of Music*, (Lawrence – Kansas, 1982).