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Measurements of vibrato parameters in long sustained crescendo notes as sung by ten sopranos

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Abstract

Two high pitched and long sustained notes, F5 and A5, were selected from an aria for soprano in ten commercial recordings of G Verdi's opera Aida. Both notes are sung without any instrumental accompaniment and with a crescendo. These audio examples were analyzed with regard to fundamental frequency, vibrato rate, vibrato extent, intonation and sound level and the relationship between these parameters was examined. The results reveal that vibrato rate differed significantly between the tones in most of the singers and confirm Prame's observations that vibrato rate tends to increase exponentially toward the end of tones. Moreover, both vibrato extent and mean F0 often varied systematically with sound level. The regularity of the vibrato tended to be greater at F5 than at A5.

Introduction

Research on vocal vibrato has a long history reaching back to the 1930s when Seashore analysed the vibrato in singers and instrument players (Seashore, 1938). In his writings, he presented the first accurate definition of the physical and musical meaning of vibrato: "good vibrato is a pulsation of pitch, usually accompanied with synchronous pulsations of loudness and timbre, of such extent and rate as to give a pleasing flexibility, tenderness, and richness to the tone."

Although his measurements were not as accurate as those presently available, most of his conclusions are still valid. Thus, many of the more recent contributions to this topic have verified his results (Dejonckere et al., 1995).

Yet, measurements of vibrato rate, henceforth VR, have yielded diverging results as has been pointed out by several authors (Shipp et al., 1980; Hakes et al., 1987; Horii, 1989). This was partly explained by the findings of Prame (1994, 1997). He accurately measured three characteristic parameters of vibrato: rate, extent and intonation, i.e., the mean of the fundamental frequency, henceforth MF0. Using a sonogram analysis, he examined the variations of these parameters in time in ten singers' performances of Franz Schubert´s Ave Maria. The results revealed that VR typically tended to increase according to an exponential function toward the end of tones. Analyzing tones with duration of 1 to 2 s he found that this increase extended over about 10 vibrato cycles. Given a VR of 5 Hz, 10 vibrato cycles will take 2 s. Thus, in most cases the increase of VR extended over the entire duration of the tone. In music, tones considerably longer than 2s sometimes occur. Such tones would represent a rewarding material for a further study of VR versus time. The aim of the present investigation was to realize such a study. Thus, VR, vibrato extent, henceforth VE, and MF0 will be examined. The results will be compared with those reported by Prame.

Recordings

Ten commercial recordings of the aria "O patria mia" from the third act of G Verdi's opera *Aida* were selected for analysis. The time span between the oldest and the most recent recording was 65 years (Table 1). Two long tones sung at the pitches of F5 and A5 (bar 5 and bar 54) were selected for analysis, see score in Figure 1. In the score, the woodwinds are sustaining a tone at the beginning of both these tones. However, in practise the soprano singers generally make a *fermata* on these notes, such that they sing most of them without accompaniment.

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Table 1. Name, recording reference and year for the selected ten sopranos.

Singer	**Recording reference**	**Recording year**
Montserrat Caballe	EMI (7 47271 8)	1974
Maria Callas	EMI (7 49030 8)	1955
Maria Caniglia	EMI (7 63331 2)	1946
Zinka Milanov	RCA (GD 86652)	1955
Aprile Millo	SONY (S3K 45 973)	1991
Birgit Nilsson	EMI (7 63229 2)	1967
Rosa Ponselle	RCA (GD 87810)	1928
Leontyne Price	DECCA (417 416-2)	1962
Renata Tebaldi	DECCA (440 239-2)	1952
Anna Tomowa-Sintow	LASERLIGHT (14 121)	1993

Method

The ten recordings were transformed to sound files by means of the Music Match software (Gleiser & al., 1998) and the two tones were isolated. The duration of the tones varied between 3.5 and 7.5 s. The Corr subroutine of the Swell software was used for the fundamental frequency (F0) tracking (Gleiser & al., 1998) and the resulting F0 curves were lowpass filtered at 10 Hz. Figure 2 shows an example.

To visualize the variation of the VR over time the same procedure was then repeated, except for the application of the LP filter. Figure 3 shows an example of the result. In some cases the VR values during the first second of the audio file were eliminated since the accompanying instruments prevented a reliable F0 tracking. Yet, the remaining part of the selected notes was long enough for accurate examination of vibrato parameters versus time.

Vibrato extent and MF0 were analyzed using Prame´s strategy. Thus, for each vibrato cycle the extreme F0 values were measured from the F0 curve. MF0 was obtained as the smoothed running average of two adjacent extremes.

The variation of sound level over time was

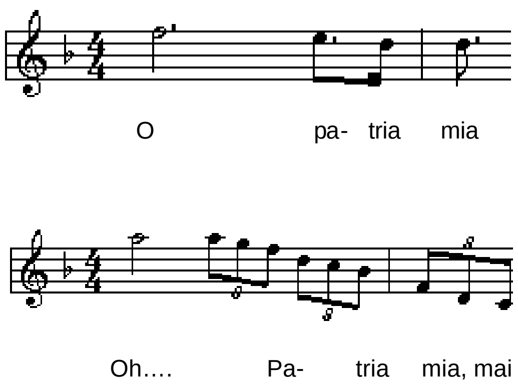

Figure 1. Excerpts from the aria "O patria mia" (G. Verdi's opera Aida) from which tones F5 and A5 were selected.

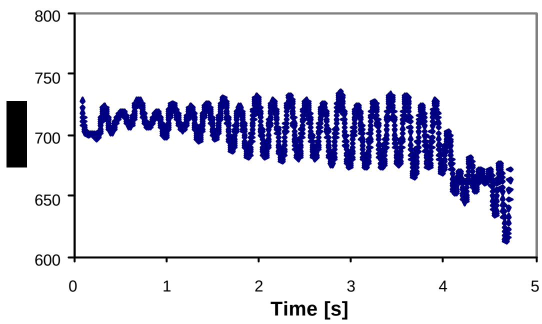

Figure 2. F0 tracking of the tone F5 as sung by Montserrat Caballé.

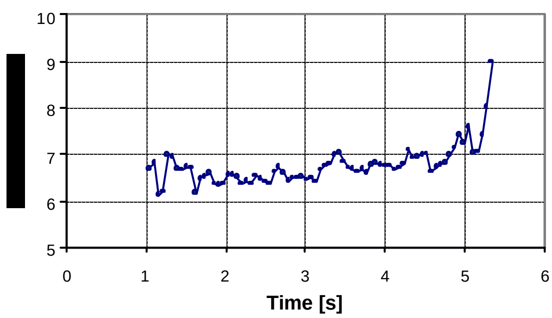

Figure 3. Vibrato rate versus time for the pitch F5 as sung by Leontyne Price.

calculated by the Extract subroutine in the Swell program package. In this way, an RMS value was obtained with a full wave rectification. This RMS value was then lowpass filtered at 200 Hz (Gleiser & al., 1998).

Results

F0 trackings

The F0 measurements yielded very clear curves of F0 versus time as was illustrated in Figure 2. The figure shows an example of irregular vibrato undulations occurring in the beginning and at the end of the tone, a phenomenon that was observed in many cases. This caused some difficulty in deciding where the vibrato measurements should start. It can also be seen in the figure that the vibrato cycles are not perfectly regular, even if the beginning and the end of the tone are disregarded. Such variation of both extent and waveform were common in most of the twenty tones examined. Possibly, the high pitch, the extended duration and/or the pronounced crescendo enhanced these irregularities.

Vibrato rate

As was illustrated in Figure 3, VR tended to increase with time, thus corroborating Prame's observations from performances of F. Schubert´s *Ave Maria*.

Table 2 and Figure 4 show the mean VR for the two tones as sung by the ten singers. In calculating these means, the vibrato cycles appearing during the first second were omitted. Likewise, to avoid the part of the tone that

Table 2. Mean vibrato rate (MVR), standard deviation (SD), changes of vibrato rate over time (dVR/dt) and squared correlation coefficients (r^2) for both tones.

Pitch	**Singer**	**MVR** Hz	**SD** Hz	**dVR/dt** Hz/s	r^2
F5	**Caballé**	5,8	0,2	-0,15	0,19
	Callas	5,5	0,3	0,23	0,45
	Caniglia	6,5	0,3	0,31	0,30
	Milanov	6,0	0,3	-0,10	0,14
	Millo	5,7	0,4	0,36	0,76
	Nilsson	6,0	0,4	-0,30	0,34
	Ponselle	6,7	0,3	0,16	0,18
	Price	6,6	0,2	0,10	0,27
	Tebaldi	6,5	0,3	0,08	0,03
	Tomowa-S.	6,7	0,4	0,04	0,00
F5 Mean	6,2	0,31	0,073	0,266	0,460
SD	0,45	0,07	0,21	0,22	0,246
A5	**Caballé**	5,5	0,3	-0,02	0,01
	Callas	5,2	0,2	0,14	0,46
	Caniglia	7,0	0,3	-0,16	0,12
	Milanov	6,3	0,4	-0,13	0,14
	Millo	5,5	0,2	-0,01	0,00
	Nilsson	6,9	0,9	-0,72	0,56
	Ponselle	7,1	0,3	-0,03	0,01
	Price	6,8	0,8	0,29	0,31
	Tebaldi	6,1	0,1	0,04	0,06
	Tomowa-S.	6,6	0,4	-0,23	0,32
A5 Mean	6,3	0,39	-0,083	0,199	0,371
SD	0,70	0,26	0,27	0,20	0,260

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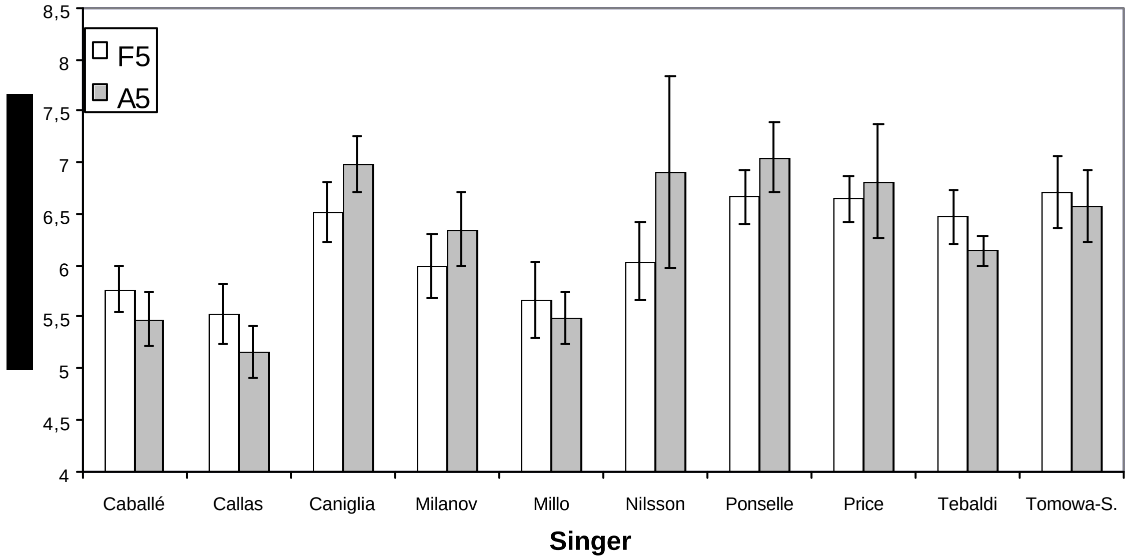

Figure 4. Singers' mean vibrato rate for the two tones analyzed. The bars show ± 1 standard deviation.

contains the vibrato tail, the final ten data points of the VR curve were eliminated from these calculations. This left a section of the tone that varied between 2 s and 6 s in duration.

Within singers, the mean VR (MVR) differed somewhat between F5 and A5. The rate was higher at A5 than at F5 in five singers and lower in five singers. The maximum difference, 0.9 Hz, was observed for Nilsson and the smallest, 0.1 Hz, for Tomowa-Sintow. In most singers, the difference exceeded the 99% confidence interval.

The MVR amounted to 6.2 Hz (SD 0.45) and 6.3 Hz (SD 0.70) for the pitches F5 and A5, respectively. The variation between singers was greater for the higher pitch. These values are similar to those observed by Prame (1994). The SD of the vibrato within the individual singer ranged from .1 and .9 Hz. Both of these extremes occurred for the higher pitch.

To examine the change of VR over time, VR was plotted as function of time, and the best liner fit was determined. The slope and correlation coefficient of these fits are listed in the same table. It can be seen that the VR tended to change in different ways during the tone. In most cases, the correlation was quite low, being greater than .44 in four cases only. In three of these cases, the VR increased with time, and in one it decreased.

A more detailed analysis of the relationship between VR and time was carried out by applying Prame's method. Thus, the period time was measured for the ten final vibrato cycles and converted to VR values. Then, the VR was normalized with respect to the mean rate appearing prior to the ten final cycles. Figure 5 shows the resulting normalized VR (NVR) averaged across all singers and both tones. The relationship could be approximated by an exponential function:

$$NVR = 1 + 0{,}19e^{0{,}28x} \qquad -9 \leq x \leq 0$$

where x is the number of the vibrato cycle, x=0 for the last cycle. The squared correlation for the two tones pooled was r^2= 0.82, but it was considerably higher for F5 (r^2=0.95) than for A5

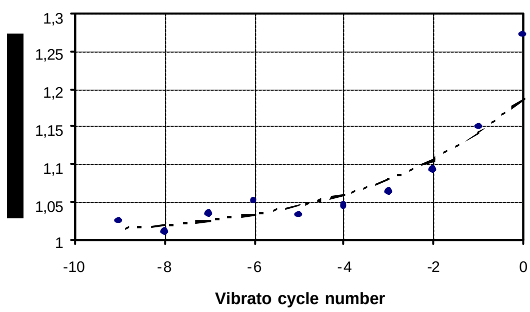

Figure 5. Average of all singers and both tones of the normalized vibrato rate versus vibrato cycle number for the last ten vibrato cycles.

Table 3. Minimum and maximum values of the vibrato extent (Min and Max VE), total change of vibrato extent (dVE) during the tone, changes of vibrato extent over time (dVE/dt) and squared correlation coefficients (r^2) for both tones.

Note	Singer	Min VE (cent)	Max VE (cent)	dVE (cent)	dVE/dt (cent/s)	r^2
F5	**Caballé**	24	75	51	16	0,89
	Callas	25	54	29	3,8	0,30
	Caniglia	24	62	38	8,9	0,36
	Milanov	23	79	56	10	0,84
	Millo	43	66	23	2,6	0,21
	Nilsson	25	70	45	5,6	0,22
	Ponselle	32	49	17	1,2	0,08
	Price	19	61	42	5,2	0,56
	Tebaldi	32	88	56	5,5	0,18
	Tomowa-S.	18	73	55	18	0,90
A5	**Caballé**	18	98	80	13	0,93
	Callas	32	65	33	5,4	0,39
	Caniglia	28	56	28	6,9	0,43
	Milanov	13	54	41	4,5	0,41
	Millo	44	102	58	3,3	0,06
	Nilsson	14	77	63	23	0,72
	Ponselle	9	35	26	1,9	0,21
	Price	14	37	23	0,2	0,00
	Tebaldi	36	61	25	1,6	0,10
	Tomowa-S.	17	45	28	4,5	0,43

Table 4. Minimum and maximum values of the intonation (MinF0, MaxF0), total change of MF0 (DMF0), changes of MF0 over time (dMF0/dt) and squared correlation coefficients (r^2) for both tones.

Note	Singer	Min MF0 (cent)	Max MF0 (cent)	dMF0 (cent)	dMF0/dt (cent/s)	r^2
F5	**Caballé**	-35	15	50	-11	0,86
	Callas	-32	42	74	8,2	0,61
	Caniglia	-28	34	62	16	0,72
	Milanov	-11	60	71	12	0,83
	Millo	-38	-8	30	3,3	0,23
	Nilsson	-5	71	76	14	0,78
	Ponselle	-32	11	43	-5,3	0,11
	Price	-37	8	45	6,0	0,72
	Tebaldi	-60	-7	53	6,5	0,33
	Tomowa-S.	-2	27	29	-3,1	0,09
A5	**Caballé**	-6	-42	-36	-4,0	0,38
	Callas	14	90	76	13	0,62
	Caniglia	-16	8	24	2,4	0,10
	Milanov	17	58	41	7,9	0,78
	Millo	-46	78	124	-21	0,58
	Nilsson	44	81	37	-2,0	0,03
	Ponselle	17	43	26	-0,1	0,00
	Price	1	39	38	1,1	0,04
	Tebaldi	-26	-1	25	3,6	0,20
	Tomowa-S.	10	51	41	0,7	0,00

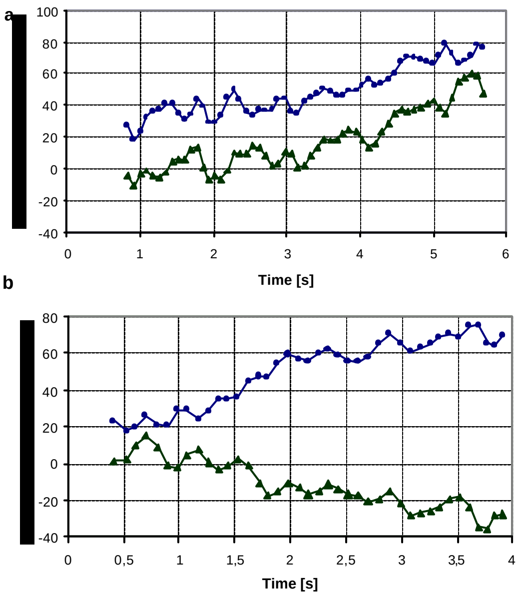

Figure 6. Values of vibrato extent (circles) and MF0 (triangles) versus time for the pitch of F5 as sung by a) Zinka Milanov and b) Montserrat Caballé.

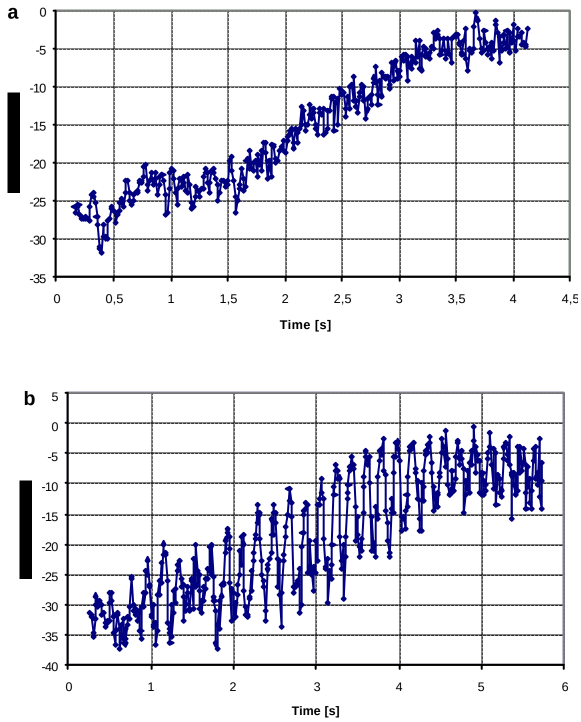

Figure 7. Sound level versus time for the pitch of F5 (a) and A5 (b) as sung by Montserrat Caballé.

(r^2=0.65). The equation indicates that, on average, VR was increased by about 20% at the end of these tones. Thus, if the mean VR at a distance of 10 vibrato cycles from the end of the tone was 6.0 Hz, it was 7.2 Hz for the final vibrato cycle.

These results show that the equation proposed by Prame gave a good approximation of the data for the tone of F5. On the other hand, the constants differ (0.15 instead of 0.19, and 0.59 in stead of 0.28). However, Prame reported that the constants varied somewhat depending on the particular selection of singers. In addition, the style of the musical composition may be relevant.

Vibrato extent and MF0

The VE tended to increase over time in both tones analyzed. As shown in Table 3 the increase varied between 17 and 80 cents and in many cases it could be approximated by a linear function of time with a quite high correlation, maximum r^2=0.93.

Also with respect to the mean F0, a linear change with time was observed in many cases, particularly for the pitch F5 (Table 4). The change ranged between 24 and 124 cents, a surprisingly high value. Both positive and negative shifts of MF0 with time were observed. The maximum average rate of MF0 change was 16 cents/s.

The VE showed a significant correlation with MF0 in some cases, as illustrated in Figure 6. In some cases both increased with time (Figure 6a) and in other cases VE increased while the MF0 decreased (Figure 6b). In some singers, VE and MF0 showed a similar variation with time in both tones.

Sound level

As both tones analyzed are marked *crescendo* in the score, an increase of sound level with time was expected. Figure 6 shows sound level versus time for both tones as sung by one of the singers. The vibrato was associated with small fluctuations of sound level in some cases (Figure 7a) and with great fluctuations in other cases (Figure 7b). The latter case would depend on the frequency distance between the strongest spectrum partial and the formant closest to it. In most cases, the increase of sound level with time could be described by a linear function, as illustrated by the high correlation shown in Table 5. This indicates that a crescendo is generally realized by a linear increase of sound level with time. On average this increase amounted to 4.1 dB/s.

Table 5. Total change of sound level (dSL) during the tone, mean rate of sound level change over time (dSL/dt) and squared correlation coefficient (r^2) for both tones.

Note	Singer	SL (dB)	dSL/dt (dB/s)	r^2
F5	**Caballé**	26	7,0	0,93
	Callas	20	4,5	0,63
	Caniglia	15	4,8	0,80
	Milanov	24	3,6	0,82
	Millo	22	4,7	0.83
	Nilsson	15	4,0	0,64
	Ponselle	13	3,9	0,71
	Price	23	4,0	0,78
	Tebaldi	14	3,0	0,33
	Tomowa-S.	22	6,6	0,65
A5	**Caballé**	30	5,5	0,74
	Callas	10	2,3	0,31
	Caniglia	5	0,56	0,04
	Milanov*	15	--	--
	Millo	27	6,5	0,84
	Nilsson	15	4,7	0,59
	Ponselle	17	4,1	0,71
	Price	17	3,0	0,57
	Tebaldi	10	1,1	0,23
	Tomowa-S.	20	4,3	0,71

(*) No values available for this case because the singer sang a *messa di voce* instead of a *crescendo*.

Correlation between vibrato parameters

In some cases, VE, MF0 and sound level were correlated. Table 6 shows the correlation between these parameters for all tones analyzed. The VE and MF0 showed a clear correlation in four cases and in two of these the correlation was negative, thus implying that an increase of the extent was associated with a decrease of MF0. At F5 six cases of a correlation between extent and sound level were found, and for A5 only two. Also with regard to MF0 and sound level, 6 cases of a clear correlation was found for the F5 pitch, and for A5 only three, two of which were negative.

Discussion

Seashore's analyses of the vibrato included Rosa Ponselle who also was included in the present study. Seashore observed a VR of 6.9 Hz and a mean extent of 48 cent for this soprano. We found a mean rate of 6.7 Hz and 7.1 Hz for the pitches F5 and A5, respectively, and an extent ranging between 32 and 49 for F5 and between 9 and 35 for A5. These discrepancies are small and can be caused by different methods of measurements as well as by analysis of different tones.

It is generally assumed that the VR is constant within a singer. Yet, the mean VR was found to differ to some extent between the two pitches analysed. The greatest difference was 0.9 Hz, which would be clearly perceptible and also smaller differences would be possible to notice. In seven of the singers, the difference exceeded the 99% confidence interval. Thus, our material does not support the idea that the mean VR remains constant within a singer.

Also some other vibrato data differed between the pitches F5 and A5. For example, there were fewer cases of a correlation between vibrato extent, MF0 and sound level for A5 than for F5. It

Table 6. Values of the squared correlation coefficient (r^2) for the relations among vibrato extent (VE), intonation (MF0) and sound level (SL).

	F5			**A5**		
	VE-SL	**MF0-SL**	**VE-MF0**	**VE-SL**	**MF0-SL**	**VE-MF0**
Caballé	0,88	-0,85	-0,80	0,92	-0,43	-0,64
Callas	0,44	0,53	0,28	0,31	0,74	0,13
Caniglia	0,61	0,67	0,53	0,13	0,07	0,17
Milanov	0,79	0,75	0,83	--	--	0,23
Millo	0,31	0,18	0,01	0,20	-0,43	--
Nilsson	--	--	0,21	0,64	-0,12	0,32
Ponselle	0,06	0,32	--	0,13	--	--
Price	0,66	0,70	0,29	--	--	0,30
Tebaldi	0,32	--	0,06	--	--	0,06
Tomowa-S.	0,66	-0,57	0,13	0,40	--	0,13

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may be relevant that the pitch of A5 is close to the upper limit of a soprano's pitch range.

Most of the singers changed MF0 during both tones. Pitch glides during tones have been observed in previous research and have been interpreted as an expressive means (Rapoport, 1996). The MF0 glide during the tones, averaged across singers, was almost 50 cent which is well above the JND for pitch. It seems an interesting question to what extent these MF0 glides are perceived as changes of the pitch or merely as contributing to the expressivity of the performance. In cases of a joint increase of sound level and MF0, the MF0 increase may be driven by the increase of subglottic pressure producing the increase of sound level. The effect is generally assumed to be about 2-6 Hz/cm H_2O (Titze, 1989). A doubling of subglottic pressure tends to produce a 10 dB increase of sound level. Assuming a subglottic pressure of 15 cm H_2O at the beginning of F5, the pressure increase for a 10 dB increase of sound level would be 15 cm H_2O. This would produce an increase of MF0 on the order of 30 to 100 Hz, corresponding to about 70 to 230 cent. The increases of MF0 fall within this range suggesting that they may have been produced by the increase of subglottal pressure.

Conclusions

The measurements presented in this investigation complement previously published data in the sense that they concern very long sustained tones sung in a high pitch range. This allowed accurate measurements of vibrato parameters within each note. The results revealed that these parameters have a more complicated behavior than was known before. First, our findings did not support the idea that the mean VR remains constant within a soprano's higher pitch range. Second, both vibrato extent and mean F0 often varied with sound level. Third, the regularity of the vibrato tended to be greater at F5 than at A5. These findings may reflect differences in the pitch control system at these pitches.

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