Measurements of the vibrato rate of ten singers

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The vibrato rate for ten singers, all singing Schubert's Ave Maria, was measured on sonograms. Commercially available CD records were used to insure that the vibrato originated in a real musical performance. It was found, that the vibrato rate typically increased at the end of each tone, +15% in average, while no typical structure could be found in the beginning of a tone. Disregarding the increase of vibrato rate toward tone endings, the mean rate across singers was 6.0 Hz. The average variation between maximum and minimum rate within an artist is about ±8% of the artist's average.

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INTRODUCTION

Carl E. Seashore and his many co-workers at Iowa University carried out a true pioneering work, when they in the late 1920s and the early 1930s studied many different aspects of the (at that time) unexplored vibrato. Their main emphasis was laid on the vocal vibrato. They designed ingenious instruments for analysis and the knowledge that they collected is still largely considered to represent the basic knowledge in this area. They published their findings in a great number of articles (see Seashore, 1932, 1936, 1937, 1938).

After Seashore, the research changed from massive effort to isolated studies concentrating on one or a few facets of vibrato. Also the experimental conditions changed completely: "Much of Seashore's studies analyzed singers performing a musical work, whereas contemporary studies had subjects sustaining a vowel sound on a designated pitch. Further, contemporary singer subjects were recorded in heavily sound-treated rooms affording little or no reverberation, which may also have affected vibrato rate." (Hakes *et al.*, 1987).

During the last decades, many authors have pointed out the remarkable discrepancies of published figures on vibrato rate (e.g., Shipp *et al.*, 1980; Hakes *et al.*, 1987; Horii, 1989), and attempts to relate the vibrato to physiological functions have been hampered by this vagueness of the vibrato rate data.

The main physical correlate of Western operatic vibrato is a modulation of voice fundamental frequency (Horii, 1989). The resulting modulation of the frequencies of the spectrum partials induces as a secondary correlate, an amplitude modulation of the partials (Sundberg, 1982; Horii, 1989; Meyer, 1991). The amplitude modulation of the strongest partials results in a modulation of the overall sound level, which may or may not be in phase with the frequency modulation. Other physical vibrato correlates may also occur. A concomitant rhythmic variation of the vocal tract shape can sometimes be observed in singers during vibrato singing; such variations cause modulation of formant frequencies and hence modulation of the amplitudes of the spectrum partials (Sundberg, 1987; Rothenberg *et al.*, 1988). Another phenomenon which would produce vibrato like pulsations is a concomitant modulation of the subglottal pressure, the major tool for regulation of vocal loudness; also such a modulation would produce mainly amplitude modulation of the spectrum partials (Shipp *et al.*, 1984; Shipp *et al.*, 1990).

The present investigation concentrates on the frequency modulation aspects of vocal vibrato. The overall aim was to describe the vibrato variability in a musical context as opposed to laboratory conditions. For this reason we resorted to Seashore's method of using material recorded in a real musical context. The findings presented in this article seem to explain the essence of the above-mentioned discrepancies regarding singers' vibrato rates, thus increasing the possibilities of a thorough, scientific understanding of the vibrato.

The frequency modulation underlying a vibrato has the following characteristics: rate, extent, and waveform. The two first characteristics seem clearly relevant to perception. The focus of this study is the vibrato rate. Three aspects of vibrato rate were analyzed, (1) the intra-tone aspect, showing measurements of the inverse of vibrato cycle duration within a tone; such data produce curves showing how the vibrato rate changes during the course of a tone, (2) the inter-tone aspect, showing how the average vibrato rate for the individual tones changes during a piece of music, and (3) the inter-artist aspect, showing how the average of all tones varies among different artists.

I. MEASUREMENTS

For the analysis, we selected prominent contemporary artists, singing in the Western classical music tradition. Real musical performances were selected from commercially available CD records. This implies that no usable measurements can be made of SPL or vocal loudness. An efficient comparison of different artists' vibrato requires that a piece of music is selected which (1) has been recorded by many artists, (2) is sung with a great vibrato extent, and (3) in a slow tempo, thus providing a great number of vibrato cycles. Furthermore, it is advantageous that the piece has been recorded also with bowed instruments, as these instruments also produce a substantial frequency modulation vibrato for comparison with vocal vibrato.

Taking the above requirements into considerations we chose *Ave Maria* by Franz Schubert, D839 (Fig. 1). CD records of ten singers were selected for analysis (Table I).

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FIG. 1. Music score of Franz Schubert's song Ave Maria (D839). The notes selected for measurements are numbered 1 to 25.

The accompaniment was performed on different instruments. Of these, harp and piano do not interfere with the measurements of the solo voice while orchestra and, particularly, choir may cause difficulties.

As the frequency range of *Ave Maria* is no more than 13 semitones, each singer could be assumed to sing in a comfortable pitch range. Given the musical character of the piece, it could be further assumed that the same was true with regard to intensity and tempo. Thus the data can be assumed not to reflect any extreme vocal conditions for the singers.

Only those tones were selected for analysis that were long enough to provide reliable data. These tones are shown in Fig. 1, numbered in consecutive order (1–25). Measurements were made on time spectrograms as displayed on a KAY DSP Sona-graph, Model 5500 (set-up: frequency range: DC-8 kHz, analysis format: spectrographic, transform size: 1024 pts., analysis window: hamming, and time axis: 100 ms). Using time cursors on the screen the time from one wave trough to the next was measured. Such a measurement can be made with an accuracy of about ± 6 ms corresponding to approximately $\pm 5\%$ in vibrato rate for a single vibrato cycle. As the positions of the two cursors were alternated from wave trough to wave trough, the same accuracy of ± 6 ms applied also to sequences of vibrato cycles, thus reducing the error in vibrato rate estimate.

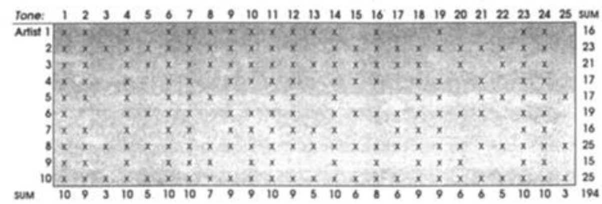

FIG. 2. List of tones that were possible to analyse with regard to vibrato rate.

All vibrato cycles for the 25 tones were measured for all artists. It turned out to be difficult to identify the first clear wave trough of a tone in many cases. In such cases even a faint indication of the first vibrato cycle was accepted. In some cases, the intensity at the end of certain tones, typically before a rest, was too low to allow measurement of vibrato rate; hence, these tones were excluded from the calculation of averages. Thus out of the selected 10×25 tones, all vibrato cycles could be measured in 194 tones, see Fig. 2. Note that for tones 3 and 25, data were obtained from three singers only, thus limiting the reliability of intersubject means.

II. RESULTS

Figure 3 presents typical results, showing data for artist 8. The variability, described in terms of the inverse of *single* vibrato cycles, is considerable, ranging from 4.6 to 7.4 Hz in artist 8. These values can be compared with the extremes within the entire population of single vibrato cycles observed in all ten singers, 4.6 and 8.7 Hz. Thus, the variation range of the vocal vibrato rate seems to be almost one octave, from 4.5 to 9.0 Hz.

However, as can be seen in the figure, vibrato rate varied during the course of the tone. While the cycles pertaining to the *head* (beginning) of the tones do not show any typical deviations from those pertaining to the following cycles, the cycles appearing in the *tail* (ending) of the tones, show a typical increase in vibrato rate over the last 1–5 cycles. The

TABLE I. The ten artists singing Ave Maria by Schubert.

Artist	Voice classific.	Key	Age of artist	Recording year	Language	Accomp.	Tempo (Quarter note duration)
1	Soprano	Bb4	37	1975	German	Piano	1.95
2	Soprano	Bb4	42	1990	German	Orchestra	2.18
3	Soprano	Bb4	41	1984	Latin	Harp	1.80
4	Soprano	Bb4	41	1988	German	Piano	2.13
5	Soprano	Bb4	26	1971	German	Piano	2.10
6	Mezzo	Ab4	34	1936	German	Piano	3.00
7	Alto	G4	38	1971	German	Piano	2.33
8	Tenor	C4	38	1979	German	Orchestra	2.10
9	Tenor	Bb3	35	1968	Latin	Organ/Choir	2.13
10	Tenor	Bb3	52	1987	Latin	Piano	2.53

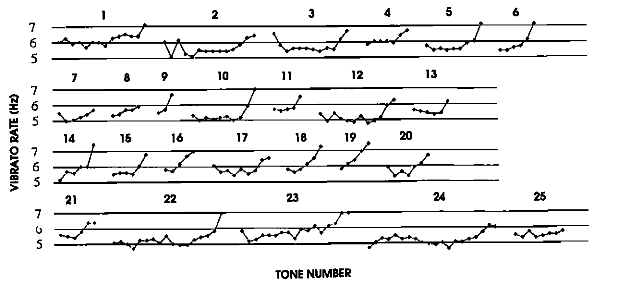

FIG. 3. Vibrato rate for each vibrato cycle in the 25 tones of singer 8.

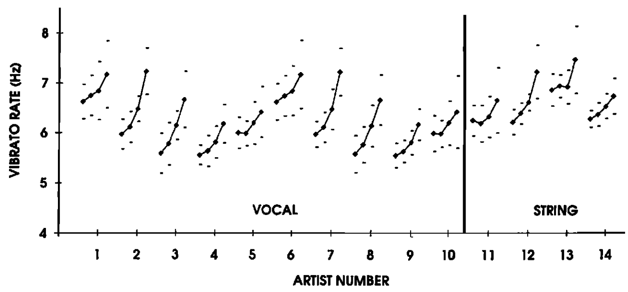

FIG. 5. Average vibrato rate and s.d. for the last 4 vibrato cycles in all 25 tones as performed by ten singers, one cellist, and three violinists.

cycle-to-cycle variation within the intermediate *body* of the tone, is moderate.

As shown by Fig. 3 there is some variability in the rate within the body between tones. Within an artist this variability can be accounted for in terms of the highest and lowest means, calculated over three consecutive vibrato cycles, which occur in any of the tones. Henceforth these means will be referred to as the body maximum and body minimum of an artist. The body minimum and maximum of artist 8 amounted to 5.0 and 6.1 Hz. Again, these values should be compared to the extremes within the entire population of body minimum and maximum rate observed in all ten singers, 5.0 and 7.3 Hz.

The observation regarding the tails turned out to be applicable to all tones, as can be seen in Fig. 4. It shows the average rates of the four final vibrato cycles for all 25 tones in the performances of all artists. Without exception, each tone showed a clear increase in average vibrato rate in the tail. However, this pattern was not observed in each individual tone of each individual artist.

This somewhat unexpected tendency to increase vibrato rate at tone endings raised the question whether or not this characteristic was specific to singing only. To investigate this, four recordings, one played on a cello and three on violins, of the same composition *Ave Maria* were analyzed by the same procedure as for the vocal performances. The same ending pattern was found, as illustrated in Fig. 5, which shows the mean and the standard deviation (s.d.) for the vibrato rate of the last four cycles of all 25 tones as performed by ten singers, the cellist, and three violinists.

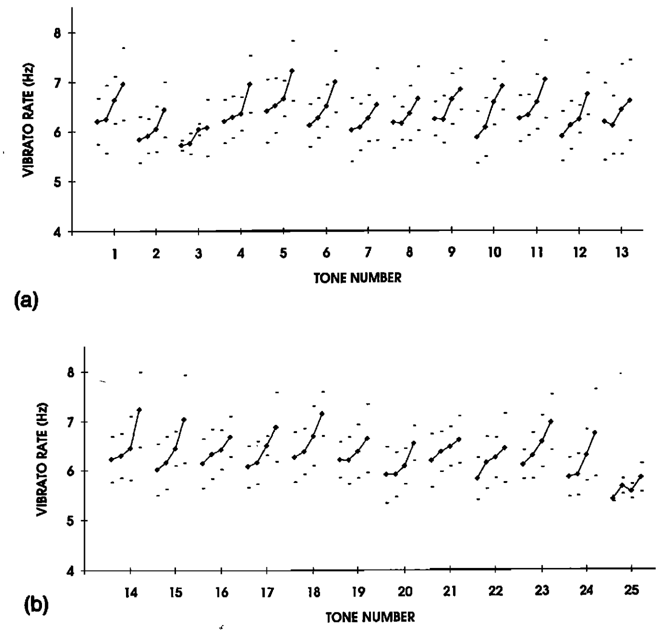

FIG. 4. (a) The ten singers' average vibrato rates ±1 s.d. for the last 4 vibrato cycles of the first 13 of the 25 tones. (b) The ten singers' average vibrato rates ±1 s.d. for the last 4 vibrato cycles of the last 12 of the 25 tones.

Figure 6 shows the mean tail form for the singers. It can be seen, that it embraces the five final cycles of the tones. If each artist's average is examined separately, the tail length varied between two and six cycles. Using a minimum square criterion it was found that the normalized vibrato rate during tone tails, averaged across all singers, f_m, could be approximated by the following equation:

$$f_m = 1 + 0.15e^{x/1.7}, \quad \text{for } -9 \leqslant x \leqslant 0,$$

where x is the vibrato cycle number.

Given the variability among the singers, the parameters of this expression can be expected to depend somewhat on the particular selection of artists.

A corresponding curve for the first five cycles of the tones is shown in Fig. 7. Only tones having at least 10 vibrato cycles were included, as at least the five final cycles had to be omitted. Thus there are fewer data points behind this figure ($N=64$) than behind the last five cycles in the Fig. 6 ($N=163$). The first cycle was also omitted because of the limited reliability commented on above. As can be seen from the figure, the beginning of the tone can almost be approximated with a straight, horizontal line.

Table II illustrates the inter-artist variability in vibrato rate characteristics for the ten singers. The average body vi-

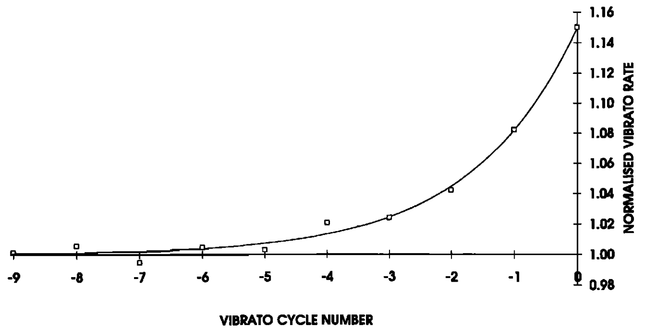

FIG. 6. Vibrato rate of the last 10 vibrato cycles in all tones, which had 10 or more vibrato cycles, calculated as the averages of the artists' averages.

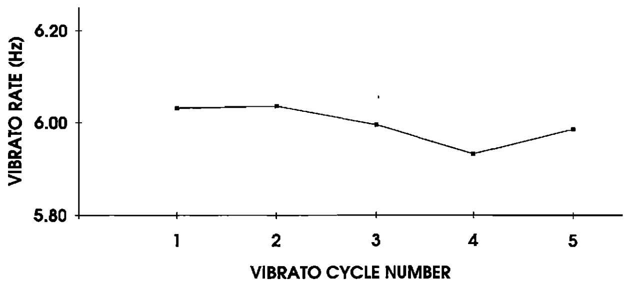

FIG. 7. First five vibrato cycles of tones having 10 or more vibrato cycles.

brato rate, averaged across all ten artists, was 6.0 Hz, maximum rate being 6.7 Hz (artist 6) and minimum rate 5.5 Hz (artists 8 and 9), i.e., +12% and −8% of the group mean.

The standard deviations show that the intra-artist variability is not negligible. The body maximum vibrato rate for the different singers varied between 5.8 and 7.3 Hz, mean 6.4 Hz. The body minimum varied between 5.0 and 6.0 Hz, mean 5.5 Hz. These mean maximum (6.4) and minimum (5.5) rates deviated by ±8% from the mean body rate of 6.0 Hz.

The variability in the shape of the tail was considerable both between and within artists. The length of the tail could vary between one and up to seven vibrato cycles. The length of the mean tail for an artist, however, was at least two vibrato cycles. The steepness of the mean tail is given in terms of the quotient between the artist's last vibrato period and the sixth period from the tone ending. The average of this quotient was 1.15, and the rate value for the final cycle varied between 6.8 and 8.7 Hz.

III. DISCUSSION

One of the main results of the present investigation was the increase of the vibrato rate toward the end of the tones. This increase was found in almost all tones as sung by all artists, regardless of whether or not the tone was followed by a rest, see Figs. 3 and 4. However, it should be mentioned that the vibrato structure could not be measured in tones sung too softly or with a too great diminuendo, see Fig. 2. On the other hand, there seems to be no reason to doubt that also very soft tones possess the characteristic tone-final increase of vibrato rate. For instance, the soft tones that could be measured did not tend to show a smaller increase of vibrato rate than louder tones.

The typical vibrato rate end structure was observed in both vocal and string performances (Fig. 5). This poses the question what the reason might be for its presence. The mechanism producing the vibrato is completely different in singing and in bowed instrument playing. Therefore, the answer must be sought either in the very basic neurophysiological behavior of the muscle activity in the performer or, at the other extreme, in the demands on musical performance raised by the perceptual system or by conventions. It would of course be interesting to know if the increase of the vibrato rate toward the end of the notes is normally being perceived. This will be addressed in a future study.

Vennard (1967) stated that a "good singer sets the tempo in multiples of his vibrato; if the tone cannot be shortened/prolonged, a good singer slows or speeds his vibrato to conform to the duration of the tone." Sundberg (1979) and d'Allessandro and Castellengo (1991) observed that frequency changes between the scale tones tend to be timed in such a manner that the change happens in phase with the vibrato, i.e., as an extension of the frequency change during the last vibrato cycle. This may lead to the assumption that (1) the vibrato rate is changed during the end of the tone, such that the pitch change happens in phase with the vibrato and (2) that for one or another reason, a speeding up of the vibrato rate is easier to perform than a slowing down; almost no example was found of a slowing down during the end of a tone. This would imply that tones followed by a rest should not exhibit the typical ending structure. As can be seen in Fig. 1 tones 3, 5, 13, 15, 17, 20, 22, and 25 all are followed by rests, while the remaining tones are followed by another tone. However, Fig. 4 shows no typical ending-structure difference depending on the note's location in the music score.

TABLE II. Various measurements for the ten singers.

	Body				Tail	
Artist	Vibrato rate average Hz	Standard deviation Hz	Maximum rate Hz	Minimum rate Hz	End quotient	Maximum rate, tail Hz
1	5.7	0.23	5.8	5.4	1.18	7.8
2	6.5	0.24	6.8	5.9	1.09	8.0
3	6.3	0.25	6.8	5.8	1.15	8.4
4	6.0	0.24	6.3	5.5	1.18	8.0
5	5.9	0.21	6.2	5.4	1.08	7.4
6	6.7	0.23	7.3	6.0	1.11	8.7
7	5.8	0.34	6.9	5.4	1.26	8.2
8	5.5	0.32	6.1	5.0	1.21	7.4
9	5.5	0.13	5.9	5.3	1.14	6.8
10	5.9	0.23	6.4	5.4	1.09	8.2
max. value	6.7	0.34	7.3	6.0	1.26	8.7
aver. value	6.0	0.24	6.4	5.5	1.15	7.9
min. value	5.5	0.13	5.8	5.0	1.08	6.8

Thus, the tendency to synchronize the pitch changes with the vibrato does not seem to explain the speeding up of the vibrato toward the end of the tones.

Even if it is difficult now to realize an explanation to the ending structure, this structure in itself partially explains the confusion regarding the vibrato rate in the past. As the vibrato rate tends to increase during the last 1–6 vibrato cycles of a tone, the average vibrato rate of a tone will depend on its duration, shorter tones showing higher average rates than longer tones; it should be appreciated that the overall duration of an entire five period tail is around 800 ms, i.e., a rather long note. As Seashore strived for including all tones in the pieces he analyzed, his material contained a relatively high percentage of short tones. Furthermore, he included all the vibrato cycles in each tone when calculating the average vibrato rate for an artist. For this reason, he arrived at rather high values. Shipp *et al.* (1980), by contrast, had singer subjects to produce tones of 4–14 s duration and cut out a 1-s long segment from the middle of these tones. Taking into account the above results, it is not surprising that Shipp, *et al.* obtained much lower averages than Seashore.

As a practical consequence of the above, the last 2–6 (in average 5) vibrato cycles should be excluded in the calculations of average vibrato rate for an artist. Provided such an average can be shown to be independent of both the character of the piece and the style of the performance it would be meaningful to define a general vibrato rate for an artist. At present, specific average vibrato rates for different artists can be compared only if they are derived from the same piece of music.

Sundberg (1987) remarked that "the rate of the frequency modulation is generally considered to be constant within a singer; that is, the singer is usually unable to change it." On the other hand, King and Horii (1993) found diverging results in an investigation where they asked nine male singers to produce a sustained 3–5 s vowel /a/ at middle C imitating the vibrato rate of 5 and 7 Hz of a synthesized /a/. The mean values were 5.2 and 5.8 Hz, and the ranges 4.6–6.3 and 4.9–6.6 Hz, respectively. It shows that (1) some voluntary variation of vibrato rate is possible and (2) a sustained vowel /a/ could not be produced with vibrato rate of $\geqslant$7 Hz. This suggests that the individual singer's interpretation of a piece of music may also affect the vibrato rate.

Seashore (1936, Chap. 8) observed a slight pitch dependence for high pitches. No pitch dependence was found in the present investigation. However, the frequency range of the *Ave Maria* amounted to no more than 13 semitones so it was probably comfortable for the singers. The tempo of the performances did not seem relevant to the vibrato rates.

The lowest body minimum rate found in this study was 5.0 Hz (Table II, 5th column). According to Seashore (1936, Chap. 8), the lower limit is the "point at which a steady quality of tone enters and wobbliness ceases so that the pulsation begins to fuse, is not a sharp point, but varies for different listeners, different singers, and other variables in tone." This point appears to lie somewhere between 4.5 and 5.0 Hz. However, some values deviating considerably from these rates occur. For example, in Verdi's *Macbeth* (Act 4: "Una macchia è quì tuttora!," the second note from the end, CDC 7 47730 2, originally recorded in 1959) Maria Callas showed a body minimum rate of no more than 4.1 Hz. When played back in isolation, this rate does not sound as a vibrato.

At the other extreme, Amelita Galli-Curci has a body maximum rate of 7.9 Hz in a recording from 1916/1917 (Verdi's *Rigoletto*: "Caro nome," BMG 09026 61413 2, 1993). By comparing the vibrato rate of famous singers of today with those of yesterday we have the impression, that body maximum vibrato rate above 7 Hz will be rather unusual today, whereas several examples of such fast rates have been observed in recordings made earlier in this century. This suggests, that the vibrato rate also might be dependant on the musical preferences and that it thus would not be meaningful to try to establish mean vibrato rate figures for male and female singers as such. However, one cannot exclude the possibility that the high vibrato rate sometimes observed in the past was caused by shortcomings of the recording equipment of those times. It is also interesting to note that Seashore expected the opposite evolution (Seashore 1938, last page of Chap. 4). He envisioned that through research in this field it would be possible in the future for singers to increase their vibrato rate by 1 Hz.

IV. CONCLUSIONS

The vibrato rate tends to increase according to a typical pattern covering the last vibrato cycles of a tone both in vocal and bowed instrument performance, +15% in average in the vocal case. This average pattern was observed for all 25 notes analyzed, although the pattern was not necessarily found in each single tone of each single artist. No typical vibrato pattern could be observed in the beginning of the tones. As a consequence, one may not be able to rely upon previously reported averages of vibrato rate. If the increase of the vibrato rate toward the tone endings is disregarded, the mean rate across the singers was found to be 6.0 Hz. The average variation between maximum and minimum rate within an artist is about ±8% of the artist's average.

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