Vibrato Performance Style: A Case Study Comparing Erhu and Violin

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Abstract. This study compares Chinese and Western instrument playing styles, focussing on vibrato in performances of Chinese music on the erhu and on the violin. The analysis is centered on erhu and violin performances of the same piece; comparing parameters of vibrato extracted from recordings. The parameters studied include vibrato rate, extent, sinusoid similarity and number of humps in the vibrato f0 envelope. Results show that erhu and violin playing have similar vibrato rates, and significantly different vibrato extents, with the erhu exhibiting greater vibrato extent than violin. Moreover, the vibrato shape of the erhu samples was more similar to a sinusoid than that of the violin vibrato samples. The number of vibrato f0 envelope humps are positively correlated with the number of beats for both erhu and violin, suggesting that erhu and violin players share similar vibrato extent variation strategies.

Keywords: vibrato feature analysis, vibrato performance style, chinese music, cross-cultural comparison

1 Introduction

Every musical genre and instrument has its own performance style(s) which can be hard to capture succinctly in a few words or sentences. As one of the expressive features important to performance style, vibrato is applied extensively across different musical genres and instruments, especially in singing and bowed-string instrument playing. To investigate the difference in vibrato style between Chinese and Western music performance, we use the erhu[3], pictured in Figure 1, and violin as a case study. We present a computational analysis of vibrato in the same piece of music performed by erhu and violin players.

Research on vibrato in Western music dates back to the beginning of the 1930s, when Seashore analysed vibrato in the singing voice and instruments [1]. Much vibrato research has been devoted to the singing voice. Prame reported the vibrato rate and vibrato extent of Western singing voices [3][4]. He found

[3] The erhu, a traditional Chinese musical instrument, is a two-stringed fiddle. The erhu is considered by many to be the Chinese violin. Like the violin in Western musical culture, the erhu plays a central role, and is often viewed as symbolizing Chinese musical culture.

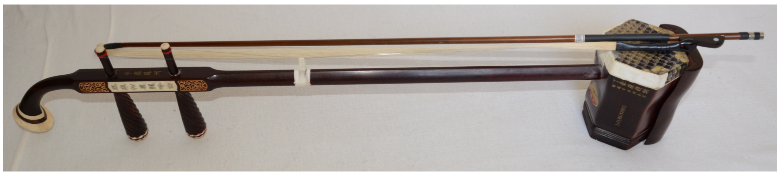

Fig. 1. Photo of an erhu.

that the vibrato rate across 10 singers averaged 6.0Hz, with a vibrato extent of 71 cents. Bretos and Sundberg examined the vibrato in long crescendo sung notes [5], and confirmed Prame's finding that the vibrato rate increased towards the end of the note. The means with which singers changed the vibrato rate as they tried to match to a target stimulus was explored in [6]. Mitchell and Kenny presented research on how singing students improved vibrato by examining the vibrato rate and extent[10]. Bloothooft and Pabon found that the vibrato rate and the vibrato extent became more unstable as singers aged [9].

The perception of vibrato has also been subject to research. The relationship between vibrato characteristics and perception in Western singing was examined by Howes et al. [8]. In [2], d'Alessandro and Castellengo showed that pitch perceived for short vibratos were different from that for long vibrato tones, and proposed a numerical model consisting of a weighted time average of the f0 pattern for short vibrato pitch perception. In [7], Diaz and Rothman showed that vibratos considered to be good (as rated by subjects) were the most periodic ones, and also that vibrato extent was the dominant factor for determining the quality of the vibrato.

The primary vibrato features examined have primarily been vibrato rate and extent, using various techniques. Relevant vibrato detection, estimation methods can be found in [12]. Distinct from previous studies, Amir et al. used self-defined parameters obtained from the spectrum and vibrato autocorrelation, instead of vibrato rate and extent, in order to assess the vibrato quality of vocal students [11]. Some researchers have also focused on the synthesis of vibrato. For vibrato synthesis, Järveläinen suggested that the accurate control of the vibrato rate is much more important than control of vibrato extent [13]. Verfaille et al proposed a generalised vibrato effect generator by introducing spectral envelope modulation to maintain the real vibrato properties [14].

Our study is a cross-cultural one comparing vibrato in erhu playing vs. violin playing. In the realm of research on Chinese music, studies on the recognition of Chinese instruments can be found in [15] and [16]. Mood classification of Chinese music was explored in [17]. Unlike for Western music, investigations into vibrato in Chinese music are scarce, and the subject area is wide open for exploration.

Vibratos can been classified into three types: pitch vibrato, amplitude vibrato, and timbre vibrato[18]. They are defined by fluctuations in pitch, amplitude and timbre respectively. In this study we investigate pitch vibrato as it is the primary factor in vibrato perception [19].

In our experiment, we consider the performances of a single piece of music by a number of erhu and violin players. We compare recordings by six different erhu players, and six distinct violin performers, all of the same piece of music. 20 notes are selected from each performance for close examination.

We utilize a number of vibrato characteristics in our study. Vibrato rate and vibrato extent are the most important parameters as vibrato rate determines the speed of the vibrato, while vibrato extent gives its depth. Vibrato structure is represented by vibrato sinusoid similarity. As for the form of the vibrato, the envelope hump number, extracted from vibrato f0 envelope, is used to assess the variation in vibrato extent.

Applications of vibrato characteristics studies includes vibrato detection [20] and synthesis [21], instrument recognition, performer recognition [22], and automatic characterization of Chinese music.

We expect that the vibrato characteristics will help reveal the differences in musical genre and instrumental styles. It is our aim to answer the following questions:

1. What are the vibrato characteristics of erhu players?
2. What are the vibrato characteristics of violin players performing Chinese music?
3. Is there any difference between the ways erhu players and violinists play vibratos when performing the same piece of music?

The remainder of the paper is organized as follows: first, the data selection method, including performance selection and note selection, is presented; followed by the relevant methods applied to the extracting of vibrato parameters. Next, the results and discussions, then the final conclusions, are presented.

2 Data

2.1 Performance Selection

It has been posited that vibrato is influenced by several factors including musical context, tone length and musical expression [4]. To investigate vibrato differences that are introduced by erhu and violin and minimize the effect of other factors, comparisons are made between performances of the same piece of music, and the same notes within the piece.

We choose a well known Chinese piece called *The Moon Reflected on the Second Spring*[4]. This piece of music describes the sufferings of a blind composer, and is idiomatic of Chinese traditional music.

The 12 performances that form the focus of our study are shown in Table 1. Performances 1 to 6 are commercial CD recordings by professional erhu players. These six erhu performers are famous in the erhu music community, and they have each received systematic education in music conservatories. Performances 7

[4] There are a number of English translations for the title of this piece. The original Chinese name is 《二泉映月》and the pinyin transliteration is Erquanyingyue.

Table 1. Selected Performances

Erhu			Violin		
Index	Performer	Nationality	Index	Performer	Nationality
1	Guotong Wang(王国潼)	China	7	Laurel Pardue	U.S.A.
2	Jiangqin Huang(黄江琴)	China	8	Lina Yu(俞丽拿)	China
3	Wei Zhou(周维)	China	9	Baodi Tang(汤宝娣)	China
4	Jiemin Yan(严洁敏)	China	10	Nishizaki Takako	Japan
5	Huifen Min(闵惠芬)	China	11	Yanling Zhang(张延龄)	China
6	Changyao Zhu(朱昌耀)	China	12	Yangkai Ou(欧阳锴)	China

to 12 are recordings by six violin players. Since this piece of music was originally composed for erhu, professional violin performances of this piece on commercial CD recordings are relatively scarce. Only 8 to 10 are commercial CD recordings. 7 is a recording of an unaccompanied performance of the piece by Laurel Pardue. 11 and 12 were found online; the performers are Chinese violin pedagogues. With respect to nationality, the 6 erhu players are all from China. For violin, the 7th player is from the U.S. and the 10th player is from Japan. The other violinists are from China.

2.2 Notes Selection

The notes were selected based on the following criteria:

1. The note should not be played on an open string. Performers cannot apply vibrato to such notes.
2. The note should be of relatively long duration. Since vibrato rate is typically around 4-8Hz, if the note duration is too short it is difficult for the performer to apply vibrato, and for listeners to perceive it as vibrato. For our case study piece, a note of long duration was one lasting more than 0.5 seconds.
3. The note should be of high amplitude. If the note has low amplitude or exhibits a diminuendo, it will pose difficulties in the measurement of the vibrato parameters, especially in pitch detection. For low amplitude notes, any noise will significantly impact signal acquisition and extraction, providing less reliable data for pitch detection.

After applying the above rules, 20 notes in the first performance were selected. To make the results as unbiased as possible, the same notes were selected from other performances. When a composition is transcribed for other instruments, it is not uncommon to see some degree of changes and recomposition. All six erhu performances used almost exactly the same composition. However, the transcription for violin, while preserving most of the original composition, had introduced some changes to the erhu version. This difference is evident in Table 2 which shows the same selected 20 notes for each performance. It tells whether this note is included in the corresponding performance or not, and whether this note has vibrato. The 7th performer applied vibrato to almost all the same notes as the erhu performers. In contrast, the 8th, 9th, 11th and 12th performances

Table 2. Note selection for each performance.

Performance Number		Note Number																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Erhu	1	✓[a]	✓	✓	✓	✓	✓	✓	✓	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3	✓	✓	✓	✓	✓	✓	✓	✓	✕	✓	✓	✓	✓	✓	*	✓	✓	✓	✓	✓
	4	✓	✓	✓	✓	✓	✓	✓	✓	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	5	✓	✓	✓	✓	✓	✓	✓	✓	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓	✓	✓	✓	✕	✓	✓	✓	✓	✓	✓	*	✓	✓	✓	✓
Violin	7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	*	✓	*
	8	✕	✕	✕	✕	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	*	✓	✓	✓	✓
	9	✕	✕	✕	✕	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	10	✓	✓	*	✓	✓	✓	✕	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	11	✕	✕	✕	✕	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	12	✕	✕	✕	✕	✕	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	*	*	✓	*

[a] ✓: has vibrato. *: has no vibrato. ✕: note does not exist.

all used the same transcription. This variation did not include the first phrase, which contained the first 5 selected notes, and they were thus not found. The 10th performance, which was by a Japanese violinist, used another version. This version did not include two notes numbered 7 and 8. Thus, 218 notes were examined in total. Performers did not apply vibrato to every note. Consequently, out of 218 notes, 204 notes had vibratos.

3 Methodology

3.1 Vibrato Fundamental Frequency Extraction

The vibrato parameters were extracted from the note fundamental frequency, and the fundamental frequency obtained using the Praat [23] software. Praat performs robustly for fundamental frequency extraction of monophonic audio. The six erhu performances were monophonic and without accompaniment; the vibrato fundamental frequencies were directly extracted using Praat. For polyphonic audio, Praat cannot provide the same reliability in extracting the fundamental frequencies as for monophonic audio. Except for the 7th performance, all other violin performances had accompaniment.

For polyphonic textures, we applied the method described by Desain and Honing in [24]. With knowledge of the expected pitch, the spectrum was filtered around the pitches of the melody. As the violin melody may be close to the accompaniment, a higher harmonic was chosen for filtering instead of the violin's fundamental frequency. The method is demonstrated in Figure 2, where one of the higher harmonics is selected for filtering. The filter pass band and stop band are readily identified in a higher frequency range. This filtered area could then be used by Praat to provide robust fundamental frequency extraction.

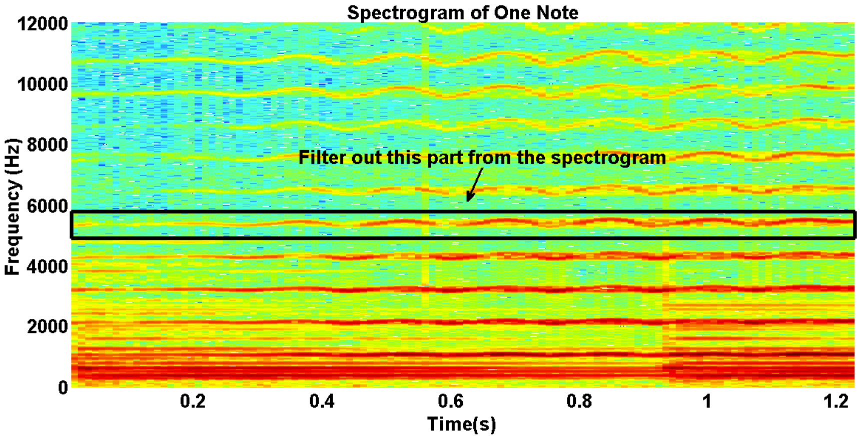

Fig. 2. Higher harmonic filtered out from spectrogram of one note.

3.2 Vibrato Rate and Extent Measurement

The vibrate rate and extent was calculated from the peaks and troughs of the vibrato fundamental frequency contour, as shown in Figure 3. Since vibrato follows a sinusoidal shape [25], the interval between one peak and one trough is assumed to be a half cycle of the vibrato period. Then, the inverse of the interval gives the vibrato rate for the corresponding half cycle. The average vibrato rate for all half cycles results in the vibrato rate for the corresponding note. The vibrato extent for one half cycle is half the difference between the peak and the trough of the corresponding half cycle. The average vibrato extent for all half cycles gives the vibrato extent for the corresponding note.

3.3 Vibrato Sinusoid Similarity Measurement

The underlying structure of a vibrato is another important aspect of vibrato research. Usually, the vibrato shape is that of a quasi-sinusoid [25]. In the present study the cross-correlation of vibrato shape and the relevant sinusoidal shape was applied to compare the similarity of the vibrato shape to that of a sinusoid. However, different vibrato notes exhibit different vibrato rates and extents, and even different phases. It is impossible to create a unique and general sinusoid as a standard reference for cross-correlation. Instead, every vibrato has its own reference sinusoid by creating a sinusoid having the same frequency as the vibrato. The vibrato sinusoid similarity was obtained as follows:

1. Convert the fundamental frequency of the vibrato from linear scale to MIDI (musical instrument digital interface) scale.
2. Apply the local regression using weighted linear least squares, and a first degree polynomial model with 80 points span to smooth the fundamental frequency, in order to get the vibrato's average fundamental frequency.

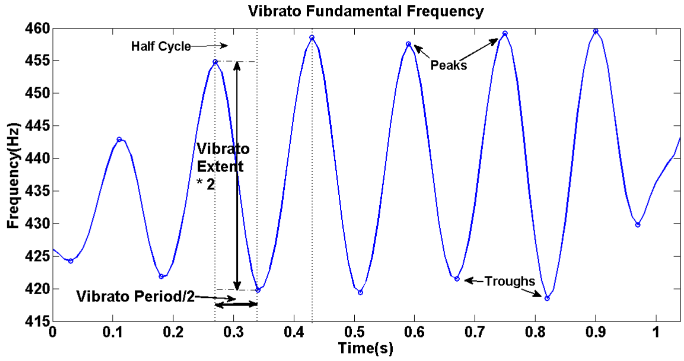

Fig. 3. Vibrato example for vibrato rate and extent measurement.

3. Subtract the vibrato's average fundamental frequency from the MIDI scale fundamental frequency to block the DC component and make the vibrato fundamental frequency centred at 0. The upper and middle parts of Figure 4 show a vibrato fundamental frequency waveform and its 0-centred fundamental frequency waveform, respectively. The data has been transformed to MIDI scale. The x-axis shows the performance time, indicating that this vibrato is played at around 49-50s into the performance.
4. Compute the FFT of the 0-centred fundamental frequency.
5. Pick the peak from the spectrum to get the vibrato frequency.
6. Use this vibrato frequency to create a sine wave, and set the amplitude of the sine wave to 1. The amplitude does not affect the final result when the normalised cross correlation is applied.
7. Calculate the normalized cross correlation between the 0-centred fundamental frequency waveform and the sine wave. The correlation index (vibrato sinusoid similarity) lies between 0-1. The larger the value, the more similar the vibrato waveform is to the sine wave.
8. Set the vibrato sinusoid similarity as the maximum of the normalised cross-correlation results.

3.4 Vibrato Envelope Measurement

Average vibrato parameters for one note have been explored extensively. However, the vibrato parameters can change within one note. How the vibrato changes is an aspect of the vibrato's characteristics. Prame showed that the vibrato rate in opera singing increased towards the end of the note [3]. Bretos and Sundberg confirmed this result for long sustained crescendo notes in opera singing [5]. In the present research, how the vibrato extent changes within one note was examined. As the analysis later in the article shows, the significant difference between erhu and violin vibrato lies in the average vibrato extent. As

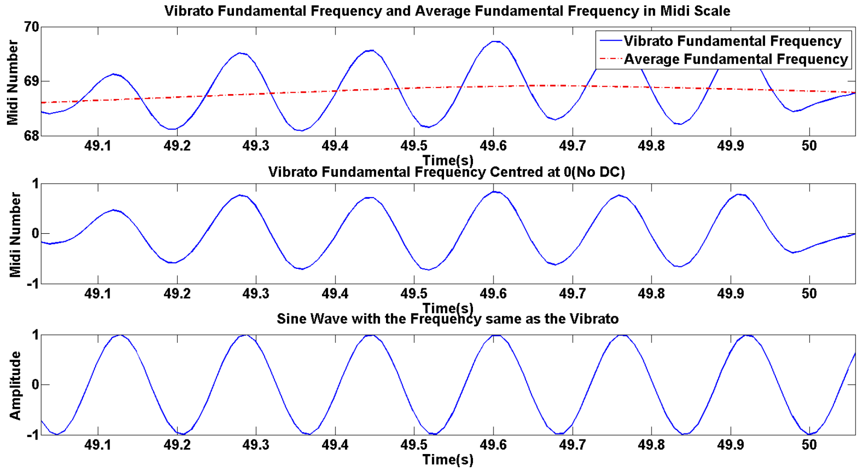

Fig. 4. Vibrato and sine wave signals for calculating the vibrato sinusoid similarity. Top: the original vibrato fundamental frequency and its average vibrato fundamental frequency. Middle: 0-centred fundamental frequency. Bottom: sine wave with the same frequency as the vibrato.

a consequence, it is interesting to examine closely the make-up of a note, which could give insight into how the vibrato extent changes within the note.

The vibrato envelope was extracted by applying the Hilbert transform to the vibrato fundamental frequency contour. The result is an analytic signal of the fundamental frequency, which is a complex signal. Then the amplitude envelope of the original signal (vibrato fundamental frequency contour) can be obtained by taking the absolute value of this analytic signal.

Finally, the envelope was smoothed by applying a moving-average filter with a 0.2-second span to filter out the noise. Figure 5 shows the fundamental frequency of one vibrato and its envelope. There are two humps in the vibrato extent envelope. For this vibrato, the vibrato extent is relatively small at the start of the note, it then reaches its first hump at around 0.2s. The extent decreases, then increases again. It reaches its second hump at around 0.75s. A decreasing trend completes the vibrato. Thus, this vibrato has two envelope humps. For each note, the number of humps in the envelope was recorded to reflect the vibrato extent variation.

4 Results and Discussions

Figure 6 shows the erhu and violin performers' mean, min and max vibrato rates on the left, middle and right, respectively. Here, the mean vibrato rate is defined as the mean vibrato rate of all of an individual performer's extracted vibratos. Min/max vibrato rate refers to the min/max value that occurred for an individual. The bar in the middle of the box indicates the median vibrato rate.

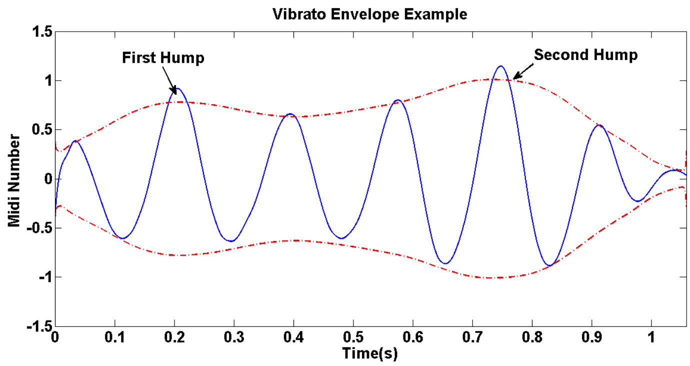

Fig. 5. Vibrato envelope of one vibrato. Solid line: fundamental frequency of the vibrato. Dashed line: vibrato envelope.

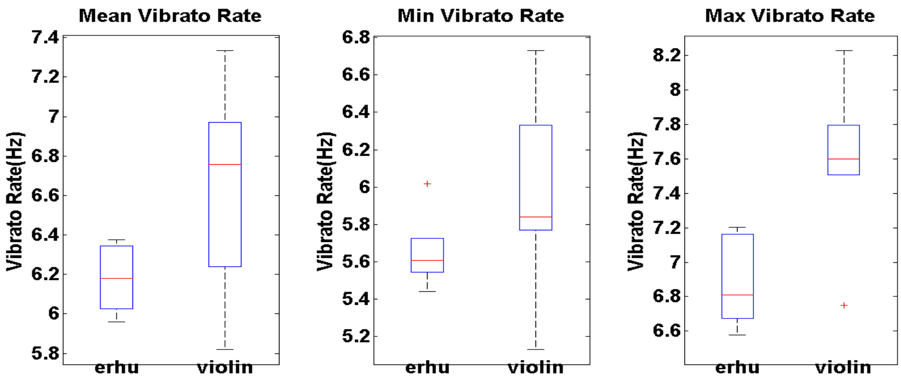

Fig. 6. Comparing the mean, minimum and maximum vibrato rates for erhu and violin.

The upper and lower edges of the box indicates the 75th and 25th percentiles. Dotted lines extend to the extreme values. Plus signs mark the outliers.

4.1 Vibrato Rate

Regardless of whether one considers the mean, min or max vibrato rates, the violin is always larger in value than the erhu. Violin performers tend to apply faster vibrato rates than erhu performers. The violin vibratos also had a wider range than those for erhu for both the mean and min rates, which means that the vibrato rate varied sharply among our violin performers. Note that although the median of the violin vibrato rate is greater than that for erhu, the lower extreme of the violin vibrato rate is lower than that of erhu. The violin performers we considered seem to demonstrate more variability in vibrato rate.

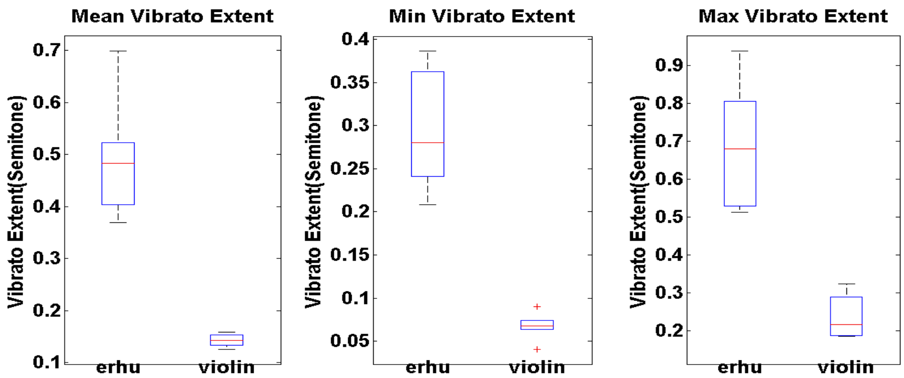

Fig. 7. Comparing the mean, minimum and maximum vibrato extents for erhu and violin.

Table 3 provides more details of the results. Erhu players have a vibrato rate ranging between 5.44 and 7.20Hz, with a mean value of 6.18Hz. Violin performers have a vibrato rate ranging between 5.13 to 8.23Hz, with a mean value of 6.65Hz.

Previous studies have shown that, in the Western classical music, the vibrato range is 4 to 12Hz [24]. Seashore noted that vibrato rates between 5 and 6Hz were more common [26]. Specifically, Prame observed that the vibrato rate range amongst 10 singers was between 4.6 and 8.7Hz, with an average value of 6Hz[3]. For violin, Seashore found that violinists had an average vibrato rate of 6.5Hz, with a small range amongst individuals; he also discovered that violinists and vocalists had similar vibrato rates. Desain et al. confirmed Seashore's result by determining that violin vibrato rates were generally around 6.5Hz [18]. The vibrato rate of violin performers is similar to the values reported in Western music studies, even though the violinists were playing Chinese traditional music.

If vibrato characteristics relate to musical styles and instruments, one might expect erhu and violin vibrato rates to be significantly different. As in [27], Ozaslan et al observed that the vibrato rate in Turkey's Mamkan music was between 2 to 7Hz, which is significantly different from that for Western music.

An ANOVA[28] analysis reveals an unexpected result, that the Chinese instrument erhu showed no significant difference from the violin in terms of mean vibrato rate ($F = 3.93, P = 0.0757$), min vibrato rate ($F = 1.43, P = 0.259$) and max vibrato rate ($F = 0.950, P = 0.0102$).

4.2 Vibrato Extent

Figure 7 shows the erhu and violin performers' mean, min and max vibrato extents on the left, middle and right, respectively. Here, the mean vibrato extent is defined as the mean vibrato extent of all of an individual's vibratos. Min/max vibrato extent refers to the min/max value of the extent of the vibratos played by an individual.

Unlike vibrato rate, the mean, min and max vibrato extent values for erhu were much larger than for violin as shown in Figure 7. Erhu performers tend to play vibratos with larger extents than violin performers. Moreover, erhu has wider vibrato extent ranges than violin for all these parameters. The vibrato extent varies more widely among erhu performers, indicating that erhu performers have more variability in their vibrato extents.

Table 3 shows that the six violin performers have vibrato extents ranging from 0.04 to 0.32 semitones, with a mean of 0.14 semitones. In the literature, Seashore found that violinists' vibrato extents, around 0.25 semitones, were half as wide as singers'. Prame stated that violin vibrato extents were no more than half that of the vibrato of singers; the ten singers he studied had vibrato extents ranging from 34 to 123 cents, with a mean of 71 cents [4]. Thus, the statement suggests that the violin extent would be no more than 17 to 62.5 cents, with a mean of 30.5 cents. In another study, the vibrato extent for Western string players was shown to be 0.2 to 0.35 semitones [29]. The vibrato extent of violin in the present study is very close to that reported in the literature. Although the violin performers were playing Chinese traditional music, their vibrato extent did not exceed that reported in the Western music studies.

Erhu performers, on the other hand, have a larger vibrato extent, from 0.21 to 0.94 semitones, with a mean of 0.49 semitones. Not only are the lower limit, upper limit and the mean value of the erhu vibrato extents larger than that of the violin, the range of the vibrato extent of erhu (0.73 semitones) is also wider than that for violin (0.28 semitones). This implies that erhu performers exercised greater variability in changing the vibrato extent than violin performers.

This observation may stem from differences in the left hand movements when playing the two instruments. For the violin, the lower left arm of the player angles up to the finger board and the vibrato movements are lateral along the horizontal finger board. For the erhu, the lower left arm of the player is more or less horizontal, and the vibrato movements are up and down along the vertical strings. The vertical alignment of the erhu strings and the corresponding hand motions may allow for larger vibrato movements.

The fingerboard exists in the violin, but not the erhu. When a violin player presses the string, the string touches the fingerboard. However, when an erhu performer presses the string, nothing else is touched. This absence of a fingerboard may give erhu performers more flexibility to create wide vibratos. This hypothesis requires further research. The ANOVA analysis shows high confidence that the mean vibrato extent ($F = 53.2, P = 2.62 \times 10^{-5}$), min vibrato extent ($F = 60.6, P = 1.49 \times 10^{-5}$) and max vibrato extent ($F = 39.9, P = 8.70 \times 10^{-5}$) are significantly different between erhu and violin players.

4.3 Vibrato Rate Range and Vibrato Extent Range

The left and middle parts of Figure 8 show the vibrato rate range and vibrato extent range for erhu and violin. The vibrato rate range for individual players results from the difference between their min vibrato rates and max vibrato rates. The vibrato extent range was obtained in a similar way. Table 4 provides further

Table 3. Statistics for vibrato rates and extents for the twelve performances.

Performance Number		Vibrato Rate (Hz)				Vibrato Extent (semitones)			
		Mean	Min	Max	SD	Mean	Min	Max	SD
Erhu	1	5.96	5.60	6.58	0.70	0.51	0.29	0.74	0.11
	2	6.34	6.02	6.67	0.64	0.70	0.36	**0.94**	0.12
	3	6.18	**5.44**	7.16	1.01	0.37	0.27	0.51	0.08
	4	6.17	5.73	**7.20**	0.90	0.52	0.39	0.80	0.10
	5	6.02	5.54	6.70	0.58	0.45	0.24	0.62	0.07
	6	6.38	5.61	6.92	0.72	0.40	**0.21**	0.53	0.06
	Average	6.18	5.66	6.87	0.76	0.49	0.29	0.69	0.09
Violin	7	6.97	5.77	7.80	0.92	0.14	0.07	0.23	0.03
	8	6.55	5.83	7.62	1.05	0.14	0.09	0.20	0.04
	9	7.33	6.73	**8.23**	0.85	0.13	0.07	0.19	0.04
	10	6.97	6.33	7.58	0.92	0.15	0.06	0.29	0.04
	11	6.24	5.85	6.75	0.83	0.16	**0.04**	**0.32**	0.05
	12	5.82	**5.13**	7.51	0.97	0.13	0.07	0.19	0.03
	Average	6.65	5.94	7.58	0.92	0.14	0.07	0.24	0.04

details. Violin performers have slightly wider vibrato rate ranges than erhu performers. However, this difference is not significant ($F = 2.54, P = 0.142$), meaning that erhu performers could have a similar vibrato rate range as violin performers. For the vibrato extent range, erhu performers have much larger values than violin performers. This difference is significant ($F = 17.6, P = 1.80 \times 10^{-3}$), meaning that erhu performers vary their vibrato extents more widely than violin performers. This suggests that erhu performers may use vibrato extent more expressively in their playing.

4.4 Vibrato Sinusoid Similarity

Vibrato sinusoid similarity is shown on the right in Figure 8. The vibrato shape of erhu performers is much more similar to a sinusoid than that for violinists. This difference is significant ($F = 14.3, P = 3.60 \times 10^{-3}$), as validated by the ANOVA analysis.

In order to try to find any relationships between sinusoid similarity and other parameters, Pearson correlation analysis has been applied. However, no significant relationships were found. The vibrato sinusoid similarity is thus uncorrelated with the other parameters. Whether the vibrato shape is related to the vibrato rate and extent needs further study.

4.5 Vibrato Envelope Hump Number

Pearson correlation shows that the number of the vibrato envelope humps is strongly and positively correlated with note duration (in beats). This phenomenon was observed in both erhu ($P = 7.92 \times 10^{-4}, r = 0.688$), as well as in violin ($P = 6.94 \times 10^{-4}, r = 0.694$) performances, indicating that erhu and violin

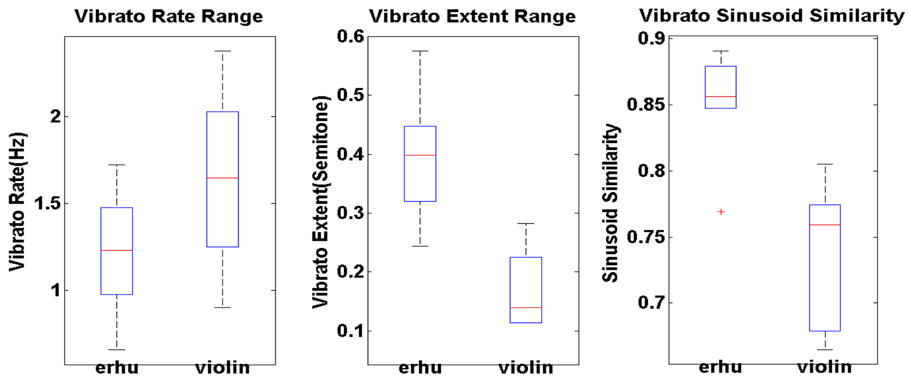

Fig. 8. Comparison of vibrato rate range (in Hz), vibrato extent range (in semitones) and vibrato sinusoid similarity for erhu and violin.

performers introduced more vibrato extent variation cycles as the number of beats increases. We noted that the r-value for erhu and that for violin are very close, meaning that erhu and violin players employed the same degree of vibrato envelope variation with the number of beats.

Figure 9 shows the number of vibrato envelope humps and note duration (in beats) indexed by vibrato number on the x-axis. It is interesting to observe that erhu and the violin vibrato hump numbers varied in the same ways. The hump numbers peak for vibratos 2, 7, 9, 13, 15 and 18, while the numbers drop for vibratos 3, 8, 12, 14 and 16. With the exception of vibratos 15 and 18, high values of note duration (number of beats) correspond to peaks in the number of envelope humps. Except for vibrato 16, low hump envelope numbers occur at vibratos with similarly low note durations. To some extent, erhu and violin players adapted vibrato extent variations to the number of beats in the same fashion. One exception is vibrato 15: it has the same number of beats as vibratos 14, 16 and 17; however, both erhu and violin players alike introduced more extent variations for this vibrato than the other vibratos.

Although erhu and violin players exhibit significantly different vibrato extents, they vary the vibrato extents in a similar way. Long notes produce typically more variations in vibrato extent. Due to human physiology, it is difficult to maintain the same vibrato rate and vibrato extent over a long period. Another explanation could be the musical context. Performers used the vibrato to indicate the beat positions. This observation warrants further exploration.

5 Conclusion

In this study, we examined the differences in vibrato playing styles on two different instruments, the erhu and the violin, for the same piece of music. Vibrato was characterized in terms of vibrato rate, vibrato extent, vibrato sinusoid similarity and vibrato envelope hump number.

Table 4. Vibrato rate range and vibrato extent range for each performer.

Performance Number		Vibrato Rate Range (Hz)	Vibrato Extent Range (semitones)	Vibrato Sinusoid Similarity
Erhu	1	0.98	0.45	0.85
	2	0.66	0.58	0.85
	3	1.72	0.24	0.77
	4	1.48	0.42	0.86
	5	1.15	0.38	0.89
	6	1.31	0.32	0.88
	Average	1.21	0.40	0.85
Violin	7	2.03	0.16	0.68
	8	1.80	0.11	0.74
	9	1.50	0.11	0.66
	10	1.25	0.22	0.80
	11	0.90	0.28	0.77
	12	2.38	0.12	0.77
	Average	1.64	0.17	0.74

Although violin performers showed slightly higher vibrato rates and ranges than erhu players, the difference is not significant. Erhu performers had significantly larger vibrato extents than violin performers. They also employed wider vibrato extent ranges than their violin-playing counterparts. The results reveal that violin players exhibited more variability in vibrato rates than erhu players, whilst erhu performers showed more variability in vibrato extents than violin performers. The vibrato shape of the erhu samples was more similar to that of a sinusoid than the violin samples. The analyses suggest that the vibrato shape is an independent and intrinsic feature of the vibrato. Erhu and violin shared the same vibrato extent hump number variation pattern; both adapted variations in the vibrato extent to the number of beats in the note.

The music piece may be traditional Chinese, but the violin players' vibrato rates and extents were consistent with those reported in the literature (for Western music). This suggests that either vibrato performance styles are more dependent on musical instrument than musical genre. Moreover, the U.S. and Japanese violinists each showed the same vibrato characteristics as the Chinese violinists. Thus, the background of the violin players may not exert a large influence on the vibrato style. Overall, the results suggest that the physical form of the instrument and how it is played may be the most dominant factor affecting the differences in vibrato style in erhu and violin playing.

While it can be difficult to completely eliminate or perfectly ensure a musician's prior knowledge of different performance practices, identifying a few performers conversant in both erhu and violin playing styles for carefully designed experiments could provide more systematic approaches to discriminating between instrument effects and performance practice in the future.

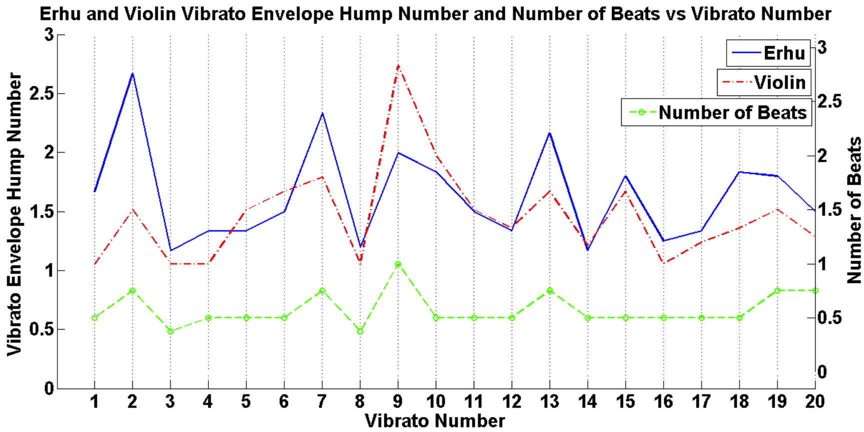

Fig. 9. Vibrato f0 envelope hump number and number of beats across vibratos.

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