Two studies of pitch in string instrument vibrato: Perception and performance responses of university and high school string players.

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Abstract:

We investigated pitch perception of string vibrato tones among string players in two separate studies. In both studies we used tones of acoustic instruments (violin and cello) as stimuli. In the first, we asked 192 high school and university string players to listen to a series of tonal pairs: one tone of each pair was performed with vibrato and the other without. Violin tones with vibrato were judged as lower in pitch than non-vibrato stimuli with the same mean frequency, more so among high school string players than university students. In the second study string players tuned their own instrument to match stimulus tones and we tested whether there are differences when performers match tones using vibrato versus non-vibrato. Participants were 30 high school string players and 30 university string players: 20 cellists, 20 violists, and 20 violinists. Performers tuned slightly but significantly lower (about three cents) when using vibrato. This outcome was consistent for tuning conditions, instruments, and experience levels.

Keywords: pitch matching | pitch perception | string instruments | string music education | string pedagogy | vibrato | music education

Article:

Almost all performers and pedagogues agree on the importance of vibrato in string playing. Achieving a relaxed and tension-free vibrato is essential in developing a beautiful and expressive tone. However, several fundamental aspects of vibrato performance remain inconsistent within the pedagogical literature. Moreover, some pedagogical views are in conflict with empirical research literature as well. Geringer, Allen, and McLeod (2010) present a broad discussion of these inconsistencies. Perhaps the most fundamental disagreement regarding string vibrato is the pitch center and direction of vibration. As is discussed in the literature below, contradictions are apparent regarding both performed and perceived pitch center. In the two studies summarized in this report, we investigated string players' perception of pitch center in string vibrato tones: first, we asked high school and university string players to make comparative pitch judgments of string (violin and cello) tones presented with and without vibrato. In the second study, we asked violin, viola, and cello players to tune their instrument to recorded vibrato tones. We studied whether pitch-matching responses performed with vibrato would be the same as responses performed without vibrato.

A primary inconsistency in string pedagogy concerns the direction of the vibrato motion. Descriptions of a backward motion (in the direction of the pegs) are more prevalent in pedagogical literature and are often notated in the form of exercises that begin on a pitch and oscillate to a pitch one half step below (Applebaum, 1986; Galamian, 1962; Hamann & Gillespie, 2004; Lucktenberg, 1994) and return to the pitch. Some suggest that this is because the human ear would perceive vibrato that travels above the pitch as sharp (Galamian, 1962; Lucktenberg, 1994). However, some pedagogues believe that the initial motion should propel forward toward the bridge (Fischer, 1997; Rolland, Mutchler, & Hellebrandt, 2000). Although Fischer described a forward direction (which would produce a higher frequency), he indicated also that the pitch should vibrate below and return to the original pitch. Only a few pedagogues report that the pitch center is found in the middle of the vibrato and that oscillations occur both above and below the original pitch (Rolland et al., 2000; Young, 1999). Fischbach (1998) concluded that the pitch center of the vibrato likely varies from performer to performer and is not consistent.

Most empirical research regarding performance of string vibrato has found that the range of vibrato frequencies extends both above and below the intended pitch (Geringer & Allen, 2004; Geringer, Allen, & McLeod, 2005; Seashore, 1938; Shackford, 1960; Small, 1936). Shackford, for example, used an electronically-generated tone as a reference pitch and had performers vibrate in tune with the constant non-vibrated tone. The professionals (members of the Boston Symphony) vibrated equally above and below what they perceived to be the pitch of the reference tone. Geringer and Allen (2004) and Geringer et al. (2005) investigated vibrato performance practice of high school and university violin and cello performers, and demonstrated that the vibrato oscillated symmetrically around the intended center of pitch, with little consistency found in initial direction of vibrato motion. These results were consistent with observations of an artist-level violinist (Allen, Geringer, & MacLeod, 2009).

A number of empirical studies investigated the pitch that listeners perceive in frequency-modulated sounds such as vibrato. Because of the necessity of stimulus control in experimental studies of perception, until recently previous research has used electronic or synthesized sound sources in place of acoustical instruments. These studies have indicated that perceived pitch corresponds closely to the mean of the frequency-modulated sound (Iwamiya, Kosugi, & Kitamura, 1983; Seashore, 1938; Shonle & Horan, 1980; van Besouw, Brereton, & Howard, 2008). Shonle and Horan extended the range of modulations to whole tones, and found that perceived pitch of those wider modulations corresponded more closely to the geometric mean of the extreme frequencies, a frequency only slightly lower than the arithmetic mean. Brown's

(1991) listeners tuned an oscillator to match the pitch of modified acoustic tones of instruments and voices. Musicians located pitch of vibrato slightly higher in frequency than did non-musicians. We found only one study published earlier than 2010 that used an unaltered acoustic string instrument for stimulus presentations. Brown and Vaughn (1996) recorded a violist performing with and without vibrato. The 11 listeners were presented with 640 trials of paired comparisons that consisted of a vibrato tone followed by a non-vibrato tone that was either higher or lower in frequency than the vibrato tone. Although the sample was limited, results were consistent with the aforementioned studies: judged pitch of vibrato tones corresponded to the arithmetic mean of the vibrato.

Recently Geringer, MacLeod, and Allen (2010) investigated music majors' perceived pitch of violin and cello tones. Recordings of acoustic instruments were used to provide both vibrato stimulus tones and non-vibrato tones that listeners adjusted to match the perceived pitch of stimuli. Vibrato stimuli were presented in one speaker, and the non-vibrato tones in the other speaker. Listeners turned a continuous response digital interface (CRDI) dial to raise or lower the frequency of the non-vibrating violin or cello tone until they heard a match with the pitch they heard in the vibrato tone. String players and other music majors (N = 72) perceived the pitch of vibrato tones very near the mean frequency of the vibrato, and string performers showed less deviation in tuning judgments than the non-string performers. Mean tuning responses of non-vibrato tones were within two cents of the vibrato stimulus means; however, most were in the flat direction (13 of 16 tones). This perhaps indicates that these musicians heard pitches of vibrato tones one or two cents lower than the arithmetic mean of the vibrato. This outcome also appears to correspond with the conclusion of van Besouw et al. (2008), who used synthesized tones and found that the range of acceptable tuning for vibrato tones was approximately 10 cents wider and predominantly in the flat direction compared to non-vibrato tones.

Purpose of the two studies

Pedagogical materials present inconsistent information regarding both pitch perception and performance of string vibrato. Until recently, almost all research investigating pitch of vibrato has used electronic stimuli. These empirical studies indicated that perceived pitch of vibrato tones corresponds closely to the mean frequency of the vibrato. In recent study using acoustic stimuli with different research methodology (method of adjustment), string players also perceived the pitch of vibrato tones very near the center (mean) of the vibrato extents. However, in the latter study (Geringer, MacLeod, et al., 2010) there were indications that vibrato may be perceived as slightly lower (a few cents) in pitch than corresponding non-vibrato tones. The two studies reported here represent a continuation of this line of studies, using a second (paired-comparisons) and third (pitch-matching) methodology to investigate pitch perception of vibrato among string players. We used acoustic instrument (violin and cello) vibrato tones as stimuli in both studies. In the first, 192 listeners heard a series of tone pairs that varied in relative tuning and use of vibrato. The primary question asked whether there are differences in pitch judgments between vibrato and non-vibrato tones. In the second study, we asked 60 high school and university string players to tune their own instrument to match presented vibrato tones. The main research question was: where will string players locate (perform) the pitch when they play with vibrato compared to matching pitches without using vibrato? In both studies we also examined possible differences between tuning conditions (sharp, flat, and in-tune stimuli), instruments, experience level (high school and university students), and gender.

Method

Preparation of stimuli used in both studies

All stimulus tones used in the studies were acoustic string tones recorded by two professional string performers. Both the violinist and cellist have graduate degrees from well-known conservatories in the United States and have performed in major symphony orchestras. Both currently teach applied previous study, and the recording procedures were described in detail (Geringer, MacLeod, et al., 2010). When producing the vibrato tones, both performers used the second finger. The violinist performed D4 (on the G string) with normal vibrato and without vibrato, as well as E5 (on the A string) with and without vibrato. Similarly, the cellist performed D3 (on the G string) and E4 (on the A string) with and without vibrato.

Pilot studies and subsequent steps taken to prepare stimuli for presentation to participants were also described earlier (Geringer, MacLeod, et al., 2010). Final stimulus tones had the following characteristics: violin tones had mean vibrato rates of 5.1 Hz with widths ranging from 30 to 36 cents; mean vibrato rates of cello tones were 5.0 Hz, with widths ranging from 24 to 28 cents. Both vibrato and non-vibrato tones were adjusted using computer software to have a mean frequency within one cent of their respective equal temperament frequencies relative to A4 = 440 Hz (without changing the vibrato widths or rates of the performers). In both studies, tones were further adjusted digitally to provide three levels of tuning stimuli: for the sharp tuning conditions (for both instruments), the mean frequency of vibrato and non-vibrato tones was raised 15 cents relative to the in-tune stimuli. Similarly, the flat tuning condition stimuli were adjusted to a mean frequency 15 cents below the in-tune stimuli.

Study 1 participants

Participants were 96 high school string players and 96 university string players and included violin, viola, cello, and double bass instrumentalists. High school students were recruited from summer music camps at two large schools of music in the southeastern United States and youth orchestras in the same region. All were in grades 9–11, had studied with private teachers a minimum of three years and were considered at or above appropriate performance level for their age. University students were volunteers recruited from classes and ensembles at the same two large schools of music. These students were undergraduate or graduate music major string students.

Study 1 method and procedures

Stimuli were presented with loudspeakers to groups of listeners. Four counterbalanced orders of presentation were used to balance conceivable effects of order. Two practice examples were included to facilitate understanding of the task. Listeners then heard a series of 12 tonal pairs: six cello tone pairs that were based on D3 (146.83 Hz); and six violin pairs of tones that were based on E5 (659.26 Hz). Violin and cello tone pairs alternated during presentation of stimuli. One tone of each pair was performed with vibrato and the other without vibrato. The second tone was in-tune, 15 cents sharp, or 15 cents flat relative to the first tone. For both cello and violin stimulus pairs, three of the pairs began with a non-vibrato tone followed by a vibrato tone that was either 15 cents sharp, 15 cents flat, or in-tune and relative to the initial tone. The other three pairs for both instruments consisted of a vibrato tone followed by a non-vibrato tone that was also 15 cents sharp, 15 cents flat, or in-tune relative to the initial tone. The rationale for 15 cents as the magnitude of mistuning was based upon the approximate width of the performers' vibratos (which ranged from 24 to 36 cents, or 12 to 18 cents in each direction). For example, if the mean vibrato frequency were 15 cents flat relative to a non-vibrated tone, then the top of the vibrato cycle would correspond approximately to the pitch level of the non-vibrated tone (thus providing a direct test of the idea that listeners might hear the top of the vibrato as the perceived pitch).

Each of the stimulus tones was three seconds in duration, with one second of silence between tones of a pair. The inter-trial interval was eight seconds. Listeners were asked to compare the pitch level of the second tone of each pair to the first tone. Participants indicated perceived intonation ratings of the second tone on a seven-point scale that ranged from flat (−3) to sharp (+3), with zero labeled as in-tune.

Study 2 participants

Participants were 60 high school and university string performers. Twenty cellists, 20 violists, and 20 violinists were evenly divided between the two levels of performance experience. The 30 high school students were recruited from a summer music camp at a large school of music in the southeastern United States. All were in grades 9–11, had studied with private teachers a minimum of three years and were considered at or above appropriate performance level for their age. University students were volunteers recruited from classes and ensembles at a second large school of music also in the southeastern United States. These students were undergraduate or graduate music major string students.

Study 2 method and procedures

Participants matched pitches individually on their own instrument in a quiet studio designed for music recording. All stimulus tones were presented using vibrato. Stimuli were presented monaurally through speakers, and participants were asked to listen and tune until they were satisfied that they matched the pitch presented. The vibrato stimulus tones sounded continuously to facilitate pitch matching. When players were satisfied with their tuning, they nodded and the tuning tone was silenced. The proctor then recorded performers' tuning responses digitally (sampled at 48 kHz with 24-bit depth).

A total of 14 tones were tuned, which included two practice trials. For six of the trials, performers were asked to match the vibrato stimulus pitch while performing with vibrato and, for the other six, tones were matched without using vibrato. The 12 experimental trials thus consisted of the two notes (D and E) with three intonation conditions (sharp, flat, and in-tune), each of which was presented twice (to be matched once with vibrato and once without vibrato). The task was completed in no more than 12–15 minutes per participant.

Cellists were asked to match pitches on tones based on D3 (146.83 Hz) and E4 (329.63 Hz). Violinists and violists matched pitches of D4 (293.66 Hz) and E5 (659.26 Hz). All performers were asked to use their second finger (III position for violin & viola, III1/2 position for cello) for both vibrato and non-vibrato tones. Tones to be matched were presented in four different orders, in order to help control for possible order effects.

Results

Study 1 results

Participant data consisted of flat (−3) to sharp (+3) ratings of the second tone compared to the first tone of each pair. Table 1 shows the means and standard deviations of listeners' judgments. It is apparent that listeners discriminated between the three directions of change from the first to second tone for both instruments (sharp M = +1.36, in-tune M = +0.10, and flat M = −1.16). It can be seen also that pitch perception ratings of vibrato stimuli were lower than for non-vibrato stimuli for all three intonation conditions for violin, and two of the three conditions for cello. The magnitude of the difference in ratings between vibrato and non-vibrato was greater for violin than for cello.

Table 1. Means and standard deviations of listeners' ratings of vibrato and non-vibrato stimulus tones (Study 1)

Stimulus	Mean non-vibrato rating (*SD*)	Mean vibrato rating (*SD*)
Violin		
Sharp	+2.04 (1.20)	+1.15 (1.66)
In-tune	+0.42 (0.99)	−0.22 (0.99)
Flat	−0.92 (2.04)	−1.47 (1.09)

Cello		
Sharp	+1.18 (1.51)	+1.09 (1.33)
In-tune	+0.13 (1.05)	+0.08 (0.73)
Flat	−1.47 (1.33)	−0.77 (1.11)

Preliminary examination of data showed no significant difference (an alpha level of .01 was used for statistical comparisons) in ratings between the four orders of presentation or between male and female respondents. These factors did not interact with any other factors. Differences were significant between experience levels. We found a violation of the sphericity assumption for the direction of change variable, and significant linear relationships between the direction of change conditions. Therefore we used a multivariate analysis of variance with direction of change conditions (sharp, flat, and in-tune) as the three variates. There was one between-subjects factor (experience level of listeners) and two within-subjects factors (vibrato condition and stimulus instrument). Significant multivariate differences were found for all three main effects: experience, vibrato condition, and stimulus instrument. However, there were significant two-way interactions between experience and vibrato condition, $F(3, 188) = 4.91$, $p < .01$, partial $\eta2 = .07$; and between instrument and vibrato condition, $F(3, 188) = 24.06$, $p < .001$, partial $\eta2 = .28$. No other multivariate interactions were significant.

Overall, these string players judged the vibrato tones as lower in pitch than corresponding non-vibrato tones, especially for the sharp and in-tune conditions. Vibrato condition, however, interacted with both experience level and instrument. Although college students judged sharp stimuli as sharper and flat changes as flatter than high school students, there was a significant univariate interaction for the in-tune stimuli, $F(1, 190) = 14.44$, $p < .001$, partial $\eta2 = .07$. The non-vibrato stimuli were judged as higher than vibrato among high school students and only a little higher among college students. Univariate interactions between vibrato condition and instrument were significant for all three directions of change. For tones that were sharper, the violin was judged as sharper than cello in non-vibrato conditions and about the same for vibrato stimuli, $F(1, 190) = 18.33$, $p < .001$, partial $\eta2 = .09$. Similarly, for in-tune stimuli, violin was heard as higher than cello for non-vibrato conditions, but was heard as slightly flatter for vibrato tones, $F(1, 190) = 15.30$, $p < .001$, partial $\eta2 = .08$. When the second tone was flatter than the first, vibrato was also rated lower than non-vibrato for violin, but the opposite was the case for cello, $F(1, 190) = 48.27$, $p < .001$, partial $\eta2 = .20$.

Study 2 results

Raw data consisted of participants’ tuning adjustments (in cents) in response to the vibrato tuning stimuli. To determine the frequency value of the tuned tones we used the arithmetic mean of the sustained portion of each vibrato and non-vibrato tone. Praat software (Boersma & Weenink, 2010) was used to analyze tones and was set to sample frequency every 2.5 milliseconds. Table 2 shows the means and standard deviations of participants' tuning responses to the stimulus tones. It can be seen that these string players tuned above the pitch to the sharp (+15 cents) stimuli, below the pitch to the flat (−15 cents) stimuli, and relatively close to the in-tune stimuli, indicating that they responded differentially to the stimuli. Additionally, it can be seen that mean vibrato tuning responses to stimuli was consistently lower in pitch (2 to 5 cents) than mean non-vibrato responses to the same stimulus tones. Further, standard deviations of the vibrato responses were greater than the non-vibrato responses for each of the six stimuli, indicating a slightly wider range of tuning responses among performers when vibrating.

Table 2. Means and standard deviations of performed tuning responses to vibrato and non-vibrato stimuli (Study 2)

Stimulus	Mean non-vibrato (*SD*)	Mean vibrato (*SD*)
D sharp	+10.45 cents (6.47)	+8.71 cents (8.29)
E sharp	+10.02 cents (5.81)	+5.88 cents (8.11)
D in-tune	+0.93 cents (5.44)	−0.77 cents (6.17)
E in-tune	−0.64 cents (5.85)	−5.37 cents (8.09)
D flat	−8.78 cents (7.67)	−10.26 cents (9.08)
E flat	−12.30 cents (5.99)	−16.61 cents (8.56)

We screened the data and verified that assumptions of the analysis of variance were met. Preliminary analyses revealed that there were no significant differences in tuning responses between stimulus presentation orders or between male and female performers ($F < 1$), nor did these factors interact with any other factors. Subsequent analysis found a violation of the sphericity assumption for the three intonation conditions ($p < .01$), and responses to the intonation conditions indicated linear relationships (correlations ranged from .24 to .54). We therefore used a multivariate analysis of variance with the intonation conditions (sharp, in-tune, and flat) as variates. There were two within-subjects factors (vibrato/non-vibrato responses and stimulus notes) and two between-subjects factors (performers' experience level and instrument). We found significant multivariate effects for response mode (vibrato vs. non-vibrato), $F(3, 52) = 10.71$, $p < .001$, partial $\eta 2 = .38$; for the two stimulus notes, $F(3, 52) = 13.13$, $p < .001$, partial η2= .43; and for the experience level of performers, $F(3, 52) = 7.43$, $p < .001$, partial $\eta^2 = .30$. Multivariate differences between the performers' instruments were marginally close to the alpha level, although not significant, $F(6, 104) = 2.84$, $p = .013$, partial $\eta^2 = .14$. No significant differences were found for any two-way or higher-order interactions between factors.

Subsequent univariate analyses showed significant differences between vibrato and non-vibrato tuning for all three stimulus conditions: sharp, $F(1, 54) = 12.71$, $p < .001$, partial $\eta^2 = .19$; in-tune, $F(1, 54) = 25.76$, $p < .001$, partial $\eta^2 = .32$; and flat, $F(1, 54) = 15.92$, $p < .001$, partial $\eta^2 = .23$. Figure 1 shows that mean vibrato tunings were consistently about three cents lower than mean non-vibrato tunings. Sharp stimuli (+15 cents) resulted in mean responses of +7.3 cents when performed with vibrato and +10.2 cents without vibrato; in-tune stimuli produced performance means of −3.1 cents with vibrato and +0.1 cents without; and tuning means for flat stimuli (−15 cents) were −13.4 cents with vibrato and −10.5 cents with no vibrato.

Significant differences were found between the stimulus notes for the in-tune and flat conditions, $F(1, 54) = 19.83$, $p < .001$, partial $\eta^2 = .27$, and $F(1, 54) = 30.86$, $p < .001$, partial $\eta^2 = .36$, respectively. Responses to the higher octave (E5 for violins/violas and E4 for cellos) were flatter than to the lower octave (D4 and D3) by approximately three to five cents. The same tendency was found for the sharp condition, but the E was only slightly flatter than the D (1.5 cents difference).

Although there was a multivariate difference between high school and university string players, univariate analyses for the individual intonation conditions did not indicate significant differences.

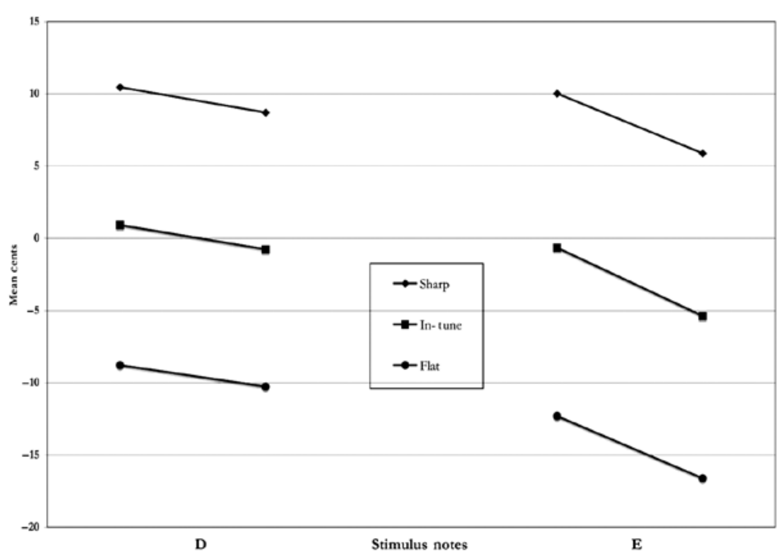

Figure 1. Vibrato and non-vibrato responses of university and high school string players to tuning stimuli

Sharp and flat stimuli resulted in marginal differences ($p = .02$) between high school and university performers, but in-tune stimuli did not. University performers tended to tune more closely to the presented stimuli; that is, they tuned approximately three cents sharper to the sharp stimuli and about three cents flatter to the flat stimuli than the high school players.

Discussion

Responses of listeners in Study 1 showed that pitches of vibrato tones were heard slightly but significantly lower than corresponding non-vibrato tones. This was the case for violin examples but not cello examples. High school string players judged vibrato tones as more flat than did university string players. In Study 2 string players did not tune precisely the same when performing with vibrato compared to non-vibrato. Across instruments, intonation conditions, and experience levels, performers tuned approximately three cents lower when vibrating. Tuning responses were also more varied when vibrating than when not vibrating. University players approximated the stimuli more closely than did the high school string players. There were also differences between stimuli in the higher octave (about 3–5 cents flatter) compared to one octave lower.

Results of Study 2 are consistent with those of recent vibrato perception studies. The performed pitches in response to vibrated tone stimuli were near the mean frequencies of the vibrato for both vibrato and non-vibrato responses. The vibrato responses were a few cents lower than non-vibrated responses, a result that appears to corroborate recent investigation of listeners' perception of vibrato tones (Geringer, MacLeod, et al., 2010; van Besouw et al., 2008). These results are consistent as well with Study 1 using the method of paired comparisons, at least for the violin. The performed responses to the tuning stimuli were similar to listeners' perceptions using the method of adjustment (turning a CRDI dial) to tune a non-vibrating tone to match a vibrato tone (Geringer, MacLeod, et al., 2010). Additionally, high school and university participants were able to approximate the given pitch for the sharp, in-tune, and flat conditions, indicating they were discriminating among the stimuli. Similar to previous research, performers with more experience (university students) were more accurate at matching the stimuli. This finding lends support to the idea that pitch matching, especially pitch matching of vibrated tones, is a learned and practiced skill.

The small but consistent difference in tuning response found in Study 2 between the higher octave and the lower octave (3–5 cents) was an outcome that has not been found in previous string research. It seems possible that the finger number and location contributed to the pitch difference. The E5 for violin and viola and E4 for cellos are located at the bottom of the neck on each instrument (either III position or III1/2 position). The proximity of the hand in relation to the body of the instruments could possibly cause performers to adjust their hand position to perform this note with vibrato. Perhaps performers moved the hand away from the body of the instrument to move more freely, which in turn altered the pitch slightly lower. The finding of a difference between octaves may have resulted from the performance task in this study compared to perception-only tasks in the previous studies.

Few studies have investigated the influence of register or location on pitch center. Previous studies that investigated conceived pitch primarily focused on tones performed in first position (Geringer & Allen, 2004; Geringer et al., 2005). Recently, string players have been found to play with wider vibrato in higher registers when compared to lower registers (MacLeod, 2008, 2010). A case study found that the vibrato of an artist level violinist was wider and tended to oscillate slightly toward the sharp side of the pitch in fifth position compared to first position (Allen et al., 2009). These results are inconclusive and additional research is needed clarify whether the register or location of the left hand impacts the pitch center of vibrato.

The performers in Study 2 tuned approximately three cents lower when using vibrato to match vibrato tones than when they performed without vibrato. Although this corresponds to results in the perception studies noted earlier, it seems appropriate to speculate regarding possible reasons for this difference. A number of factors may be influencing these musicians. As noted by Seashore in 1938, vibrato is a pulsation of pitch accompanied by changes in loudness and timbre. Modulations in tone quality and intensity, as well as tonal context, have been found to influence pitch discrimination (Geringer & Worthy, 1999; Plomp, 1976; Terhardt & Grubert, 1987; Wapnick & Freeman, 1980). The change in timbre and intensity that occurs when performers use vibrato may be related to performers adjusting pitch of their own vibrato slightly lower to match some combination of timbre, loudness and pitch changes perceived in the vibrato stimulus tone. It could be further conjectured that this might present a rationale for string players to play on the sharp side of the pitch in an ensemble context; that is, perhaps they may learn to play a few cents higher to compensate.

Further, although empirical data show that performers vibrate both above and below the conceived tone, some pedagogues advocate that the vibrato go below and back to the pitch (Galamian, 1962; Lucktenberg, 1994) and many suggest flattening exercises to help teach the correct vibrato motion (Applebaum, 1986; Galamian, 1962; Hamann & Gillespie, 2004; Lucktenberg, 1994). It is conceivable that violinists and violists who have practiced this flattening motion may have a tendency to play a slightly lowered mean pitch during vibrato. However, because cellists usually do not practice the flattening exercises prescribed for the upper strings, this does not explain their tendency to also perform a few cents flatter when using vibrato.

Regardless of factors affecting the pitch difference between the vibrated and non-vibrated tones, it should be noted that the mean difference of approximately three cents is below the threshold of a just noticeable difference (JND) between two tones (Spiegel & Watson, 1984), particularly within a musical context. Although the difference was consistent and statistically significant, it seems problematic to consider this a musically meaningful difference. Almost all musicians and skilled listeners would not perceive a difference of three cents between tones, especially when masked by the addition of modulations (in intensity, waveform, as well as frequency) present during vibrato, not to mention the presence of other instruments. If this difference is not musically meaningful, then it can be argued that, functionally, vibrato and non-vibrato share the same perceived pitch center. Future research may lead to further delineation of performed and perceived differences in vibrated and non-vibrated tones, including the influence of intensity and timbre modulation in listeners' perception of vibrato.

Results of these and future studies have implications for string music education and pedagogy (see Geringer, Allen, et al., 2010). Because vibrato is such an essential aspect of string playing, careful study of vibrato perception and performance is critical to accurately inform string pedagogy.

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