MUSICIANS CAN RELIABLY DISCRIMINATE BETWEEN STRING REGISTER LOCATIONS ON THE VIOLONCELLO

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VOCAL RANGE LOCATION IS AN IMPORTANT VOCAL affective signal. Humans use different areas of their vocal range to communicate emotional intensity. Consequently, humans are good at identifying where someone is speaking within their vocal range. Research on music and emotion has demonstrated that musical expressive behaviors often reflect or take inspiration from vocal expressive behaviors. Is it possible for musicians to utilize range-related signals on their instrument similarly to how humans use vocal range-related signals? Might musicians therefore be similarly sensitive to instrumental range location? We present two experiments that investigate musicians' ability to hear instrumental range location, specifically string register location on the violoncello. Experiment 1 is a behavioral study that tests whether musicians can reliably distinguish between higher and lower string register locations. In Experiment 2, we analyze acoustic features that could be impacted by string register location. Our results support the conjecture that musicians can reliably discriminate between string register locations, although perhaps only when vibrato is utilized. Our results also suggest that higher string register locations have a darker timbre and possibly a wider and faster vibrato. Further research on whether musicians can effectively imitate vocal range location signals with their instruments is warranted.

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WHEN HUMANS ARE HIGHLY EMOTIONAL, they often utilize a higher region of their vocal range compared to when they are less emotional (Bänziger & Scherer, 2005; Sauter et al., 2010). For this signal to be effective, humans must be able to accurately determine where someone is speaking within their vocal range. Research demonstrates that humans are highly sensitive to relative pitch location even when the speaker is a stranger. Honorof and Whalen (2005) found that when twelve participants listened to vocal tones recorded by strangers, they were reliably able to indicate the location of the tone within the speaker's vocal range. Bishop and Keating (2012) successfully replicated their findings by having 20 native American English speakers and 21 native Mandarin speakers complete a similar task of rating pitch location within a speaker's vocal range. However, they also found that English speaking participants performed the task more successfully when listening to the English stimuli than to the Mandarin stimuli, while the somewhat bilingual Mandarin listeners performed equally well with both the English and Mandarin stimuli (Bishop & Keating, 2012). Based on these results, they theorized that prior exposure to a particular population could form more accurate expectations about vocal ranges that thereby increased participants' ability to perform the task successfully (Bishop & Keating, 2012).

Research on music and emotion has frequently suggested that musical expressive behaviors often parallel and take inspiration from vocal expressive behaviors (Huron, 2015; Huron & Trevor, 2016; Juslin & Laukka, 2003; Trevor et al., 2020; Trevor & Huron, 2018; Warrenburg, 2019). Could musicians mimic vocal ethological signals associated with range location? Are humans therefore comparably sensitive to instrumental range location? Given the seeming importance of prior exposure (Bishop & Keating, 2012), it could be that only musicians have enough exposure to instrumental sounds to be able to hear instrumental range location. Therefore, our report investigates this question with participants with music training. Specifically, our goal was to determine whether instrumental range location is audible to musicians similarly to vocal range location.

The perception of instrument range location (or register) involves perceiving a fundamental frequency (f0) as well as sound-source (instrument) size, since sound-source size heavily determines overall pitch range (e.g., a violin versus a violoncello) (Patterson et al., 2010). There have been several studies investigating what acoustic features communicate sound-source size (Plazak & McAdams, 2017; Siedenburg et al., 2021) and

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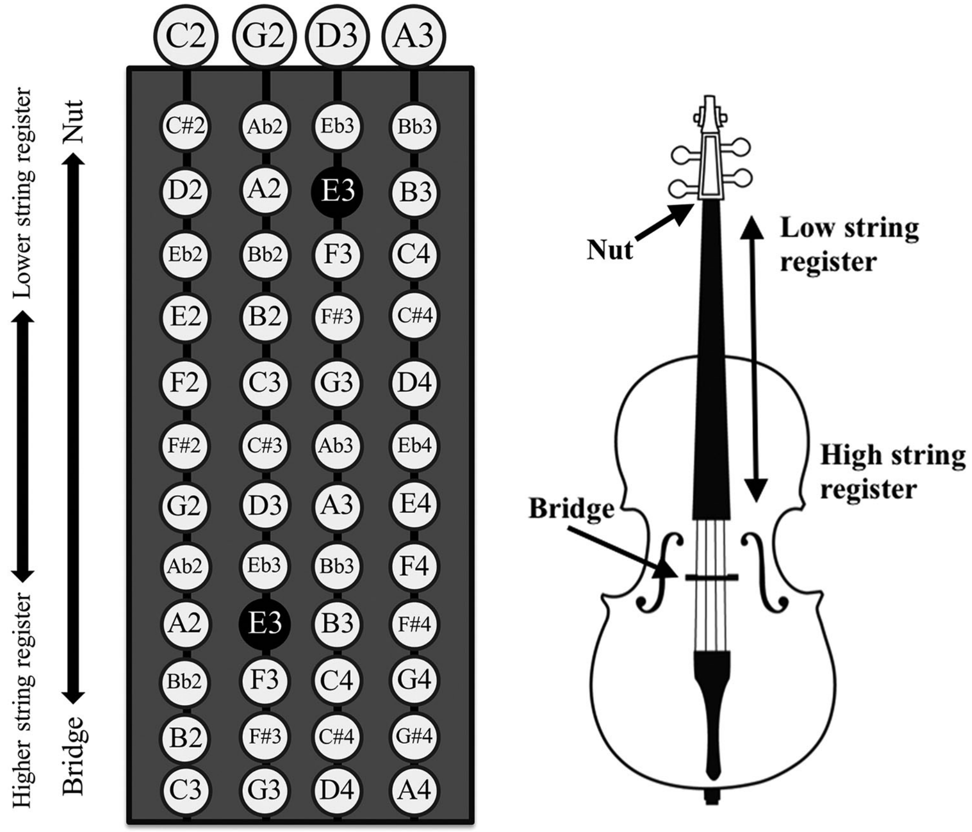

FIGURE 1. A demonstration of high and low string register on a cello in relation to the nut and the bridge. Note how the pitch E3 (labelled in white on black circles) can be played in two different places on the cello: in the middle register of the G string or in the lower register of the D string.

how sound-source size and instrument register impact other perceptual features like expressed emotion (McAdams et al., 2017) and perfect pitch (Reymore & Hansen, 2020). However, as mentioned above, such studies have not yet examined our awareness of pitch register location within an instruments' overall range. String instruments are uniquely suited to investigate whether range location is audible on an instrument because range can be explored separately from pitch, unlike on a flute where pitch and instrument register are inseparable. This division of pitch from instrument register is possible with string instruments because one can play the same pitch in different registers of higher- and lower-pitched strings. For example, on the violoncello, it is possible to play the pitch E3 in a location closer to the bridge (upper string register) on the G string, or in a location closer to the nut (lower string register) on the D string (see Figure 1). With a string instrument, we can directly compare recordings of the same pitch played in different string register locations.

Since our investigation is inspired by the perception of vocal range location, we opted to use the most voice-like classical bowed string instrument for our investigation: the violoncello (Schubert, 2019). This voice-like association could perhaps be due to the fact that the singing pitch range of most voices (from Eb2 to A5) neatly falls within the pitch range of the cello (C2 to C6) (Black & Gerou, 1998). To investigate whether musicians can hear range location on a musical instrument, we recorded three cellists playing individual pitches in higher and lower string register locations. First, in a behavioral experiment, we used the stimuli to investigate musicians' ability to aurally distinguish string register locations. Then we ran acoustic analyses on the recorded pitches to determine what timbral differences might be driven by string register location.

Experiment 1: Identification of String Register Location

METHOD

In Experiment 1, we investigated musicians' ability to identify string register location on the cello. Specifically, we tested how well musicians were able to sort cello tones into one of two categories: a tone played in a higher string register location, or a tone played in a lower string register location. The following *a priori* hypothesis was tested: Participants will be able to sort pairs of recorded pitches into either higher string register or lower string register notes demonstrating an ability to aurally distinguish string register on the cello.

Recording the Stimuli

Three professional cellists (one female) were recruited from the School of Music at The Ohio State University. For the recording session, we selected sixteen pitches that equally encompassed all four strings (A, D, G, and C). For each pitch, we notated a lower string register version and higher string register version creating sixteen pairs of notes (32 notes in total). The tempo was 60 beats per minute in 4/4 time. Each note was written as a whole note resulting in each individual note recording being 4 seconds in length (see Appendix for the sheet music). We recorded the notes in several takes, once with vibrato and once without vibrato. We included these two vibrato conditions because we suspected that vibrato characteristics might be influenced by string register and therefore could impact participant performance in the sorting task (more on this topic in Experiment 2). The cellists played the notes in a normative *arco* (bowed) style and paused between each note to prevent overlap in the audio signal. Each recording session took about an hour. Cellists were each compensated $40 (USD). We recorded in a soundproof room using a Rode NT2A microphone placed about 30 cm away from the f-holes of each cello. The recordings were captured using the program Audacity on a Mac computer as mono tracks at a sampling rate of 44,100 Hz.

Participants

Forty-eight participants (twenty-one females), took part in this study. They were all music students at The Ohio State University. Forty participants were between the ages of 18 and 22, six were between the ages of 22 and 30. The participants were recruited by email from aural skills course rosters.

Procedure

We used the javascript library jsPsych (De Leeuw, 2015) to create the online experiment interface. Participants were emailed a link to access the experiment online. When designing the experiment, we were concerned that incorporating multiple cellists, cellos, and vibrato conditions might make this already challenging timbre discrimination task too difficult for participants. Acoustical properties vary distinctively between cellos due to different types of wood, bridge designs, string lengths, and other construction and design elements (Meyer, 2009). Therefore, we opted for a between-subject design with six groups (three cellists and two conditions: with vibrato or without vibrato). To clarify, each participant heard recordings by only one of the three cellists and heard only one condition (with vibrato or without vibrato) throughout the experiment.

At the start, participants were asked to use the best quality headphones available to them. They were then given two example groups of recordings of pitches played on the cello, Group A and Group B, which were described as sounding slightly different from each other. Each example group had two pairs of recorded pitches in them: specifically, a lower and higher string register version of the pitches C4 and Gb3. Participants familiarized themselves with the example recordings. The examples were available for listening throughout the experiment. Then participants were presented with the other 14 pairs of notes (of the 16 recorded), one at a time, and asked to identify which of each pair they believed belonged in *Group B* by pressing 1 or 2 on their computer keyboard ("1" = *Note 1 belongs in Group B*, "2" = *Note 2 belongs in Group B*). Group B was the higher string register group. Therefore, participants were essentially sorting which of a pair of pitches was more likely played in a higher string register location. The order in which the notes in each pair appeared was counterbalanced by string register, and the order in which the note pairs appeared was randomized across participants. Upon completing the experiment, participants were compensated with course credit (pass/fail, worth 5% of their final grade) for their respective aural skills course in agreement with the course instructor.

RESULTS

The data were analyzed using R (R Core Team, 2017). Remember that we predicted that participants would be able to sort pairs of recorded pitches into either higher string register or lower string register pitches demonstrating an ability to aurally distinguish string register location on the cello. Answers were coded as "correct" (1) or "incorrect" (0). If the results are consistent with the hypothesis, the resulting average proportion of correct scores (amount correct / 14) should be higher than chance (0.5). The results of a test for normality (Shapiro-Wilk) suggested that the distribution of the participants' scores was not normal (p = .028) and so we used a nonparametric test. A Wilcoxon signed-rank test indicated that the results were consistent with the hypothesis in that the participants on average scored significantly higher (Mdn = 0.643, n = 48) than chance (0.5), z = 798, p < .001, r = .511. We also used a standard

TABLE 1. *Impact of Vibrato or Cellist Playing on Participants' Accuracy Scores for the String Register Location Identification Task*

	Accuracy
(Intercept)	**0.58***** [0.45, 0.71]
Vibrato	0.11 [−0.20, 0.24]
Cellist [2]	0.016 [−0.14, 0.17]
Cellist [3]	−0.04 [−0.20, 0.12]
N	48
R^2 / R^2 *Adjusted*	.070 / .007
*** $p < .001$; ** $p < .01$; *$p < .05$	CI 95%

Note. The results of a standard linear regression testing whether vibrato or cellist playing affected participants' accuracy scores for the string register location identification task. Both had no significant impact on participant accuracy demonstrating that participants performed comparably across the six experiment groups.

linear regression with lm in R to investigate the impact of vibrato and the cellist playing on the accuracy scores. The predicted value was Accuracy (proportion correct in the string register identification task) and the predictor values were Vibrato (1 = with, 0 = without), and Cellist (as a factor). The results of our regression analysis are in Table 1.

We found no main effects for vibrato (p = .109) or cellist playing (p = .835, p = .601) on the accuracy results suggesting that participants performed the task similarly well across groups, $F(4, 44) = 1.11$, p = .36. R^2 for the model was .070, and adjusted R^2 was .007. However, while the impact of vibrato on task performance was not statistically significant, further examination of the data suggests that perhaps the task is not accomplishable without vibrato. Figure 2 contains two histograms that show the accuracy scores of the participants for the string register location identification task. The left graph is a histogram of all of the accuracy scores demonstrating that the majority of the participants (31 out of 48, ~65%) were able to perform the task successfully better than chance (>50% accuracy). The right graph is a mirror histogram showing how the accuracy scores differ by vibrato condition. In the without vibrato condition, only about half of the participants scored above chance, whereas in the with vibrato condition, 75% of the participants performed better than chance. Therefore, this graph suggests that vibrato could perhaps play a crucial role in hearing string register location.

CONCLUSION

The results of Experiment 1 were consistent with our hypothesis in that participants could discriminate between lower and higher string register locations

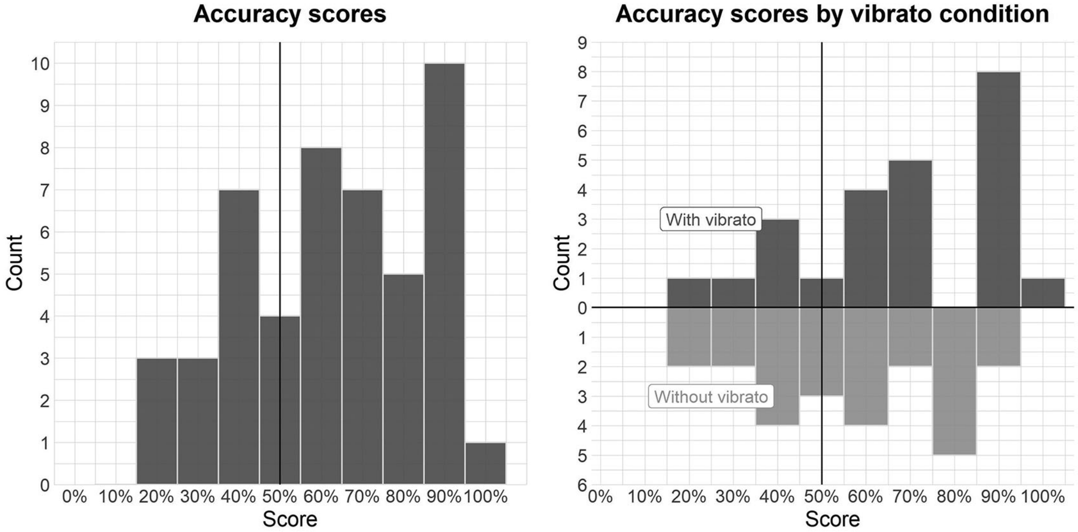

FIGURE 2. The left graph is a histogram of the accuracy scores for the string register location identification task. This graph demonstrates that the majority of the participants (31 out of 48, ~65%) were able to perform the task successfully better than chance (> 50% accuracy). The right graph is a mirror histogram showing how the accuracy scores differ by vibrato condition. This graph suggests that without vibrato, the task may not be accomplishable. In the without vibrato condition, only about half of the participants scored above chance whereas in the with vibrato condition, 75% of the participants performed better than chance. Therefore, while vibrato did not have a statistically significant effect in the regression analysis, this graph suggest that it could still perhaps play a crucial role in hearing string register location.

significantly better than chance. However, further examination of the data suggests that the task may only be accomplishable with the presence of vibrato. These results support the hypothesis that string register location may be audible to musicians similarly to how we are able to perceive vocal register location.

Experiment 2. Acoustic Features Affected by String Register Location

To follow up on the results of Experiment 1, we conducted a second experiment investigating how string register location impacts timbre. An important aspect of contemporary string sound is the consistent use of vibrato (Geringer et al., 2010). Vibrato—the addition of a small rapid pitch oscillation above and below an intended note—is considered a timbral aspect of string sound, rather than pitch related, because it does not alter the perceived fundamental frequency being played (Geringer et al., 2010). Regarding vibrato, the results of Experiment 1 pose an important question: why did the sorting task seem to rely on the presence of vibrato? How does vibrato change between the upper and lower string register? Previous research consistently demonstrates that vibrato becomes wider and faster as one moves up the fingerboard towards the bridge (Allen et al., 2009; Geringer et al., 2010; Geringer & Allen, 2004; MacLeod, 2008; Pope, 2012). Therefore, an acoustic analysis was planned with the following hypothesis: vibrato width and rate will both be significantly greater in the higher string register than in the lower string register of the cello.

Regarding other aspects of timbre, acoustic features measuring spectral distribution and noisiness have been found to be important acoustic features for distinguishing string instrument timbres (Chudy, 2016). We therefore elected to measure several features that would quantify these timbral qualities: spectral centroid, spectral rolloff, spectral flatness, and zero crossing rate (ZCR). According to string acoustics research, moving into a higher string register diminishes the higher frequency overtone content resulting in a darker timbre (Meyer, 2009). Essentially, the overall spectral distribution shifts lower resulting in a lower spectral centroid (mean of the spectral distribution), a lower spectral rolloff (the frequency at which 85% of the spectral distribution falls beneath), and less noisiness (lower spectral flatness and ZCR) (Dubnov, 2004; McFee et al., 2015; Peeters et al., 2011). Therefore, the additional acoustic analyses proceeded with the following *a priori* hypothesis: the higher string register pitches will have a significantly lower average spectral centroid, spectral rolloff, spectral flatness, and ZCR than the lower string register pitches.

METHODOLOGY

The sound files had a duration of about 4.5 seconds and were.wav files. All recorded pitches were normalized to a peak amplitude of -1.0 dB. We measured vibrato width and rate manually with the fundamental frequency visualizer in Praat shown in Figure 3 (Boersma & Weenink, 2005; MacLeod, 2008).

In the visualizer, we opened each recording and measured the frequency and time stamp of both the highest and lowest point of the fundamental frequency of a single vibrato rotation near the center of the waveform where the cellists' vibrato width and rate was most stable. We measured spectral centroid, spectral rolloff, spectral flatness, and ZCR using the Python package libROSA (McFee et al., 2015). All spectral features were measured with a sampling rate of 44,100 Hz, an FFT window size of 2,048, a frame length of 2,048, a hop length of 512, and a Hann window. The data were analyzed using R (R Core Team, 2017) with some images generated using JASP (JASP Team, 2018).

RESULTS

Regarding vibrato, recall that our hypothesis was that the vibrato rate and width would be significantly greater for pitches played in the higher string register compared with pitches played in the lower string register of the cello. To test this hypothesis, we performed two standard linear regression analyses using lm in R. The predicted values were vibrato Rate and Width and the predictor value was String Register (0 = lower, 1 = higher). The results of our regression analyses are in Table 2.

We found no main effect for string register on vibrato rate ($p = .036$; compared against the Bonferroni-adjusted value of $p < .025$), $F(3, 86) = 2.48$, $p = .067$. R^2 for the model was .08, and adjusted R^2 was .048. Specifically, while the results tend towards the predicted direction, vibrato rate did not significantly increase from lower string register notes ($M = 5.95$, $SD = 0.67$) to higher string register notes ($M = 6.31$, $SD = 0.91$) (Figure 4).

Regarding vibrato width, we found a main effect for string register location ($p = .021$) on vibrato width, $F(3, 86) = 18.45$, $p < .001$. R^2 for the model was .39, and adjusted R^2 was .37. However, the directionality of this effect was not the same for each cellist. Average vibrato width increased from low string register (cellist 1: $M = 11.78$, $SD = 2.84$; cellist 3: $M = 20.04$, $SD = 5.11$) to high string register (cellist 1: $M = 16.51$, $SD = 4.56$; cellist 3:

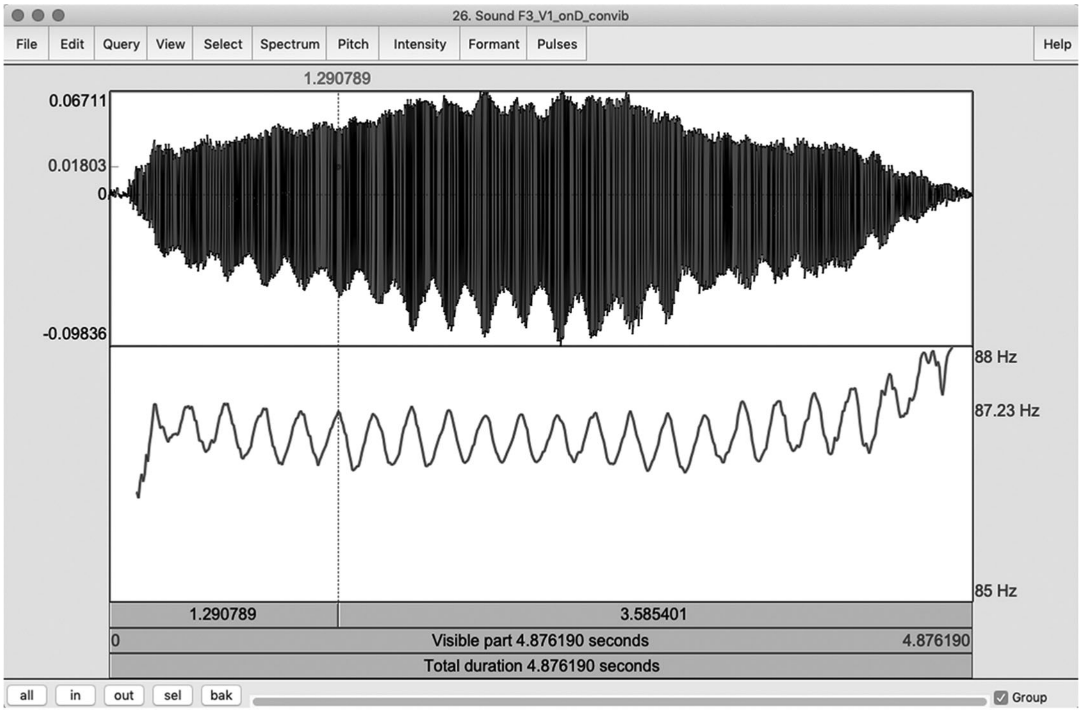

FIGURE 3. The fundamental frequency visualizer in Praat used to measure vibrato rate and width. The top panel shows the waveform of the recording, and the bottom panel shows the fundamental frequency of the waveform. The vertical line is used to select a point in time on the waveform. The selection shown here is at 1.29 seconds, as indicated above and to the lower left of the vertical line. To the right of the bottom panel, the upper and lower numbers describe the frequency range shown that encompasses the fundamental frequency of the waveform, here being 85-88 Hz. The middle number indicates the fundamental frequency at the point in time selected with the vertical bar, here being 87.23 Hz.

TABLE 2. *Impact of String Register Location on Cello Vibrato*

	Rate (Hz)	Width (Cents)
(Intercept)	**5.86** ***	**13.19** ***
	[5.52, 6.21]	[11.23, 15.14]
String Register	0.36	**2.28** *
	[0.03, 0.7]	[0.35, 4.21]
N	90	90
R^2 / R^2 *Adjusted*	.08 / .048	.392 / .37
Bonferroni corrected values: *** $p < .0005$; * $p < .025$	CI 95%	

Note. The results of a standard linear regression testing whether string register location affects the rate and width of cello vibrato. Vibrato width was significantly affected by string register location. However, inconsistent with our hypothesis, vibrato width was not always wider in the higher string register. Cellist 1 and 3 had wider vibrato in the higher string register, and cellist 2 had narrower vibrato in the higher string register. While in the predicted direction, vibrato rate was not significantly faster for the higher string register notes, inconsistent with our hypothesis.

M = 23.99, *SD* = 5.72) for cellists 1 and 3. However, average vibrato width decreased from low string register (*M* = 15.32, *SD* = 3.29) to high string register (*M* = 14.27, *SD* = 4.64) for cellist 2. In sum, while string register does have a significant impact on vibrato width, the results are not consistent with our hypothesis in that vibrato width did not always increase for the higher string register notes.

On the subject of timbre, we predicted that higher string register pitches would have a significantly lower average spectral centroid, spectral rolloff, spectral flatness, and ZCR than the lower string register pitches. While we made no *a priori* hypotheses regarding the impact of vibrato, the two conditions were accounted for in the analyses. To test this hypothesis, we performed a standard linear regression analyses using lm in R. The predicted values were spectral centroid, spectral rolloff, spectral flatness, and ZCR, and the predictor values were string register (0 = lower, 1 = higher) and vibrato (0 = without, 1 = with). The results of the analyses are shown in Table 3.

The results showed a main effect for string register location on spectral centroid (p = .0006) but no main effect for vibrato (p = .442), $F(4, 163) = 9.46, p < .001$. R^2 for the model was .19, and adjusted R^2 was .17. Specifically, consistent with our hypothesis, spectral centroid was significantly lower for higher string register pitches compared to lower string register pitches (Figure 5).

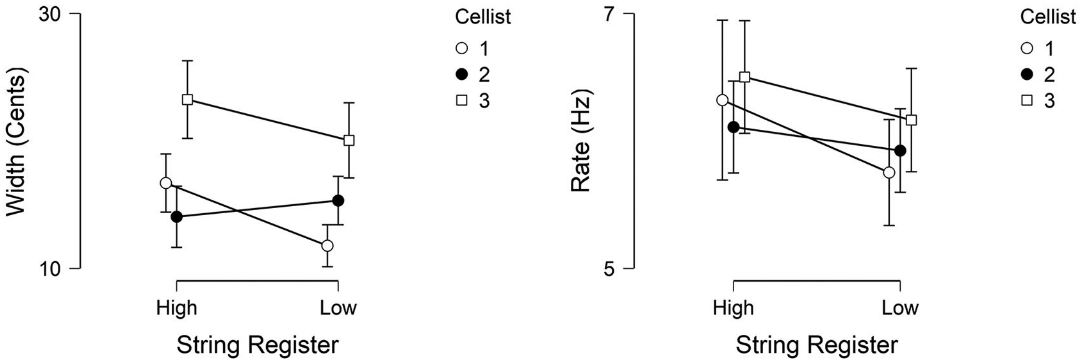

FIGURE 4. These two graphs demonstrate the impact of string register location on vibrato widths (left) and rates (right). The whiskers indicate confidence intervals of 95%. Vibrato width was wider in the higher string register for cellists 1 and 3. However, for cellist 2, vibrato was wider in the lower string register. All three cellists exhibited faster vibrato rates for the higher string register compared to the lower string register. However, this difference was not statistically significant.

TABLE 3. *Impact of String Register Location (SR) on Cello Timbre*

	Spectral Centroid	Spectral Rolloff	Spectral Flatness	ZCR
(Intercept)	**1369.91** ***	**2533.87** ***	**5.56E-04** ***	**6.39E-02** ***
	[1254.13, 1485.68]	[2351.89, 2715.86]	[4.66E-04, 6.46E-04]	[5.47E-02, 7.31E-02]
SR	**−182.17** **	**−304.25** **	−5.90E-05	**−1.27E-02** *
	[−285.72, −78.62]	[−467.02, −141.48]	[−1.40E-04, 2.12E-05]	[−2.09E-02, −4.45E-03]
Vibrato	40.39	106.49	2.11E-05	−1.94E-03
	[−63.17, 143.94]	[−56.28, 269.26]	[−5.95E-05, 1.02E-04]	[−1.02E-02, 6.31E-03]
N	168	168	168	168
R^2 / R^2 *Adjusted*	.188 / .169	.311 / .294	.331 / .314	.077 / .054
Bonferroni corrected values: *** $p < .00025$; ** $p < .0025$, * $p < .0125$				CI 95%

Note. The results of a standard linear regression testing whether string register location (SR) affects timbre as measured with four spectral acoustic features: spectral centroid, spectral rolloff, spectral flatness, and zero crossing rate (ZCR). Consistent with our hypothesis, the results show that spectral centroid, spectral rolloff, and ZCR were all significantly lower for higher string register pitches. However, while in the predicted direction, spectral flatness was not significantly lower for higher string register pitches, inconsistent with our hypothesis.

The results showed a main effect for string register location on spectral rolloff ($p = .0003$) but no main effect for vibrato ($p = .198$), $F(4, 163) = 18.37$, $p < .001$. R^2 for the model was .31, and adjusted R^2 was .29. Namely, consistent with our hypothesis, spectral rolloff was significantly lower for higher string register pitches compared to lower string register pitches (Figure 5). We found no main effect for neither string register location ($p = .148$) nor vibrato ($p = .606$) on spectral flatness, $F(4, 163) = 20.11$, $p < .001$. R^2 for the model was .33, and adjusted R^2 was .31. While tending towards the predicted direction, these results were inconsistent with our hypothesis in that spectral flatness was not significantly lower for higher string register pitches compared to lower string register pitches (Figure 5). Finally, the results showed a main effect for string register location on ZCR ($p = .003$) but no main effect for vibrato ($p = .643$), $F(4, 163) = 3.39$, $p < .01$. R^2 for the model was .08, and adjusted R^2 was .05. Specifically, in support of our hypothesis, ZCR was significantly lower for higher string register pitches compared to lower string register pitches (Figure 5). These findings were consistently observed across all three cellists (Figure 6).

CONCLUSION

We conducted this experiment to investigate how string register location impacts cello timbre considering the perceptual difference suggested by the results of Experiment 1. While tending towards the predicted direction, our results were inconsistent with our hypothesis in that vibrato rate was not significantly faster in higher string register locations compared to lower string register locations. Vibrato width changed significantly between the two string register locations but did not change in the

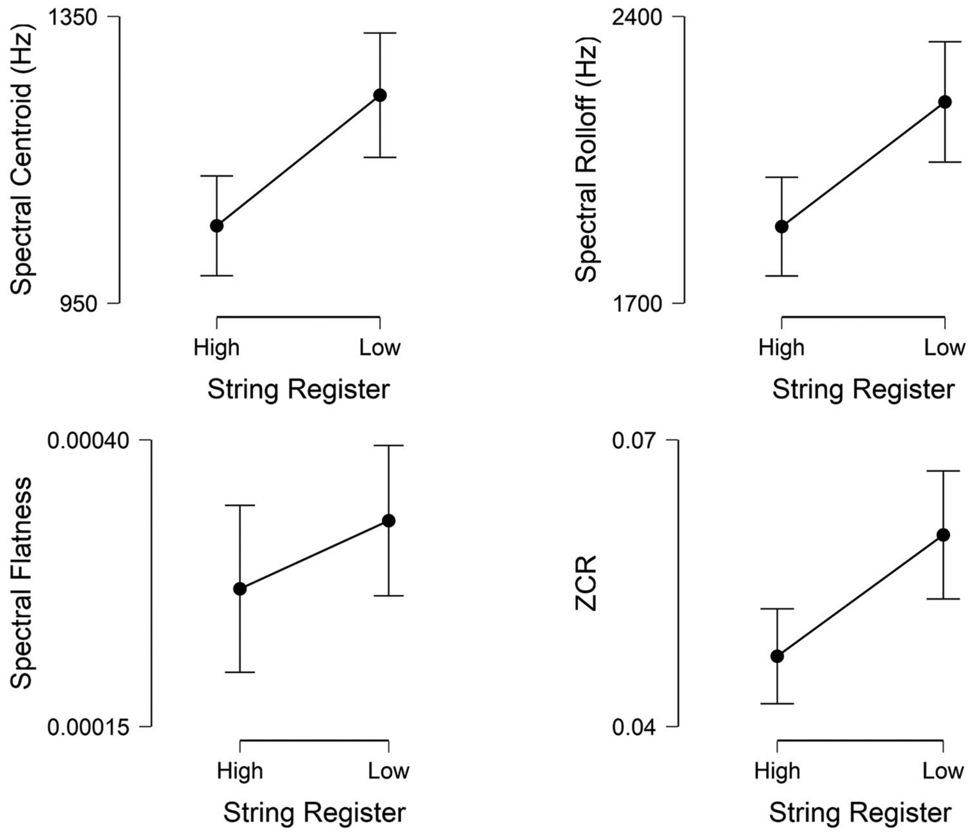

FIGURE 5. These four graphs demonstrate the impact of string register location on four acoustic features: spectral centroid, spectral rolloff, spectral flatness, and zero crossing rate (ZCR). The whiskers represent confidence intervals of 95%. The results exhibit a significantly lower spectral centroid, spectral rolloff, and ZCR for the higher string register. While spectral flatness is also lower in the higher string register, the difference is not statistically significant. These results are consistent with our hypothesis suggesting that as a cellist moves up the fingerboard into higher string registers, their sound loses more and more high frequency content and noisiness resulting in a darker timbre.

same direction across all three cellists. Cellists 1 and 3 increased their vibrato width in the higher string register, consistent with our hypothesis, while cellist 2 decreased their vibrato width, inconsistent with our hypothesis. We also analyzed four spectral acoustic features to investigate whether higher string register pitches have a darker overall timbre than lower string register pitches. Consistent with our hypothesis, higher string register pitches might indeed have a darker timbre as measured by a lower average spectral centroid, spectral rolloff, and ZCR. Inconsistent with our hypothesis, spectral flatness was unaffected by string register location. These results were consistent across all three cellists and across both the "with vibrato" and "without vibrato" conditions. Overall, the results provide support for the conjecture that the cello's sound changes significantly from the lower string register to the higher string register with a darkening timbre and likely a wider and faster vibrato.

General Discussion

This study investigates whether musicians are sensitive to string register locations on the cello similarly to how humans are sensitive to vocal range location. We conducted two experiments: a behavioral study testing the conjectured effect and an acoustic analysis experiment on how string register location impacts cello timbre. The results of the first experiment are consistent with our hypothesis that participants with music training can discriminate between string register locations significantly better than chance. However, the results also suggest that such a task may only be accomplishable with the presence of vibrato. Given that vibrato is employed almost constantly in contemporary classical performance, the results still offer support for the conjecture that in most contemporary performance contexts, string register location is indeed audible to musicians.

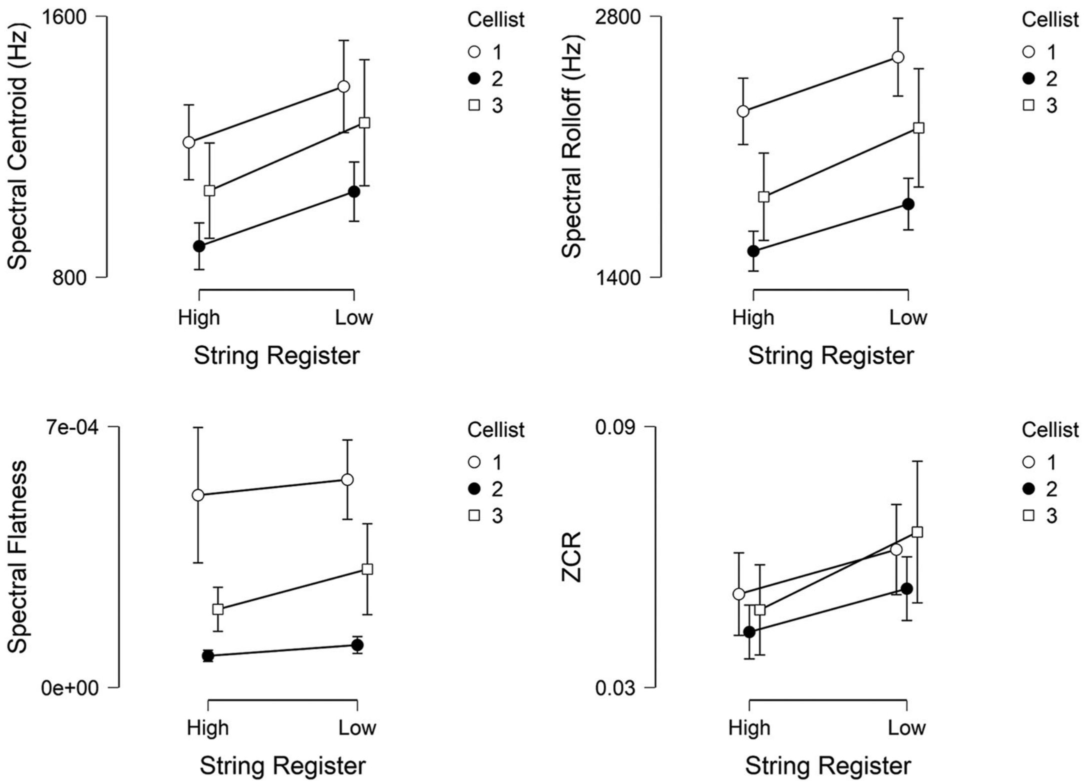

FIGURE 6. These four graphs demonstrate the impact of string register location on four acoustic features (spectral centroid, spectral rolloff, spectral flatness, and zero crossing rate (ZCR)) across the three cellists we recorded. The whiskers represent confidence intervals of 95%. As can be seen in the graphs, the effects shown in Figure 5 are observable across all three cellists.

The results of the second experiment are consistent with our hypothesis that there are marked acoustic differences between the lower and higher string registers. Vibrato width significantly differed between registers, although for two cellists it became wider in the higher string register (consistent with our hypothesis) and for one it became narrower (inconsistent with our hypothesis). The results for vibrato rate showed it increasing marginally for the higher string register. However, inconsistent with our hypothesis, these results were not statistically significant. While research shows strong trends in how string register impacts vibrato characteristics, it is important to note that vibrato can be quite unique between different players due to differences in physicality and musical preferences (Macleod, 2008). Perhaps such idiosyncrasies between players can account for the differences we found in vibrato width trends between the cellists. The higher string register pitches exhibited a darker timbre, defined here as having diminished overtones and a less noisy sound quality (Meyer, 2009). Consistent with our hypothesis, spectral centroid, spectral rolloff, and zero crossing rate (ZCR) all were shown to decrease for the higher string register. However, spectral flatness did not significantly change between the string register locations.

These results have implications for the emotionally expressive potential of string register location. Research on vocal (Dromey et al., 2015) and musical (Gabrielsson & Juslin, 1996) emotional expressiveness suggests that a faster vibrato rate could convey a higher emotionality. Regarding timbre, less high-frequency energy (darker timbre) is associated with lower energy/arousal and more high-frequency energy (brighter timbre) is associated with more energy/arousal (Eerola et al., 2012). Similarly, McAdams et al. (2017) found that instrument register is positively correlated with energy/arousal emotion ratings. Therefore, perhaps higher string register locations, which have a faster vibrato and darker timbre, could convey more intense emotions than lower string register locations. Further investigations of the emotional impressions conveyed by string register locations are warranted.

It is worth mentioning a few confounds that may have affected the results of this study. Regrettably, there was no task designed to check whether participants were wearing headphones or not. If participants chose to ignore our instructions and not wear headphones, that choice could have had a negative impact on the quality of the data. Future similar studies would benefit from a headphone test, such as the one designed by Woods et al. (2017). An additional confound is that we did not alternate which Group (A or B) participants were basing their selections on in Experiment 1. All participants were asked which note sounded the most like Group B (the higher string register pitch group). Unfortunately, due to this design issue, there could be some bias in how participants responded. Perhaps if they were unsure, they gravitated more towards the group in question (Group B). Future research might consider a design in which the pertinent group name is alternated across participants.

Overall, it does seem possible for musicians to hear string register location on the cello when vibrato is used. We hope that our findings inspire additional investigations into the perception of instrument register and its possible relationship to vocal affective signals. For example, it would be interesting to study the audibility of string register location on plucked instruments, such as guitar or electric bass, or on string instruments with different pitch ranges, such as the violin. Furthermore, while this study presents foundational findings regarding how musicians perceive string register location, it would be valuable for future research to examine how well these timbre differences are perceived by nonmusicians to shed light on whether the observed expressive musical behavior does indeed translate to listeners with less acoustically sensitive hearing abilities.

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Appendix

This is the sheet music that the cellists played from when the audio stimuli were recorded. The numbers above the notes dictate which finger should be used to play each note (1 = index, 2 = middle, 3 = ring, 4 = pinky). The roman numerals below the notes indicate what string the note should be played on (I = A, II = D, III = G, IV = C). The combination of each noted finger and string results in a common playing position–one of the numbered locations for the hand to be placed along the fingerboard codified in string pedagogy–in the intended lower or higher string register locations.