A Preliminary Investigation Into the Effect of Bell Cover and Filter on Pitch of Wind Instruments

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The Covid-19 pandemic has caused adverse effects on instrumental music teaching and concerts, including those involving wind instruments. Many schools now use bell covers and air filters during rehearsals and performances to help prevent aerosol transmission of disease. This study sought to examine if the use of these bell covers and filters might have an effect on mean instrument pitch. A sample of pitches in the low, middle, and high tessitura of each wind instrument were collected in three groups: no treatment, bell cover only, and bell cover with air filter. The data was then entered into the analytical software package "R." T-tests and Analysis of Variance were run on the data to compare the three groups. Additional comparisons of mean pitch deviation were also made as to instrument family (brass/woodwind) and note (low tessitura to high). The analysis showed that when using both bell cover and filter, there is a small degree of sharpness when compared to performing with no treatment.

The COVID-19 pandemic is the most significant event in recent world history. The first group of cases were publicly identified as coming from China on December 31, 2019; the first case discovered in the USA was on January 15, 2020 (Centers for Disease Control and Prevention, 2020). Although Western countries were slow to realize the speed of infectivity, the WHO declaration of global pandemic on March 11, 2020 quickly led to a reaction in all levels of government and civic institutions, including education. The first state in the USA to close its schools was Ohio, on March 16 (Mike DeWine: Governor of Ohio, 2020), quickly followed by the rest of the nation's educational institutions. On March 19, California was the first U.S. state to institute a "stay at home" order, followed by the other states to varying degrees.

Although it was suspected early in the pandemic that aerosol transmission was a possible cause of contagion (van Doremalen et al., 2020), research on such a means of transmission was not widely known until April 2, 2020, when the publication of a Chinese study on aerosol transmission involving victims seated at the same restaurant seemed to indicate how infectious COVID-19 was in aerosol (Lu et al., 2020). By August 7, the National Institutes of Health published research that linked the spread of COVID-19 definitively through aerosol transmission (Tang et al., 2020).

The pandemic caused an immediate, detrimental effect on both performing arts and music education, as performances and rehearsals were canceled throughout the world. Both performing artists and researchers immediately began investigating ways to remediate the aerosol spread inherent in large group music performance, especially in wind instruments. In the United States, a large group of researchers under the guidance of the National Federation of State High School Associations (NFHS) and the College Band Directors National Association (CBDNA) began research on the spread of aerosols in group music rehearsal and performance. In the second round of results released on July 31, 2020, recommendations were made that included seating musicians at least six feet apart, the use of masks, and bell covers for instrumentalists (National Federation of State High School Association, 2020b).

There already exists both experimental and educational research into these areas. Even by Monteverdi's era, it was known that inserting an object into the bell of an instrument raised the pitch, as this effectively shortens the length of the pipe (Baines, 2012). Griffin (2012) discerned that while an object placed in the bell generally sharpened the pitch, if the bell of a brass instrument is placed close to an object such as a music stand, this proximity flattens the pitch a little. The amount of sharpness from a mute inserted into the bell can raise the pitch as much as 1/4 of a half step (Baron, 2011). Snow (2006) noted that different mutes affect the pitch differently, depending on whether the mute was inserted into the bell or covered the bell.

Since the appearance of COVID-19, music education research has included investigation into disease mitigation amid efforts to keep music ensembles as active as possible. As bell coverings were discussed widely as one strategy against the spread of COVID-19, investigations began quickly to determine suitable materials for these covers and their effectiveness. Konda et al. (2020) suggested that cotton, natural silk, and chiffon were the best materials for filtration. Firle et al. (2022) recently investigated aerosol emission rates from wind instruments. In that study, it was determined that emission rates were comparable to that of singers, and that covering an instrument bell with a surgical mask did not reduce the spread of aerosols. An additional report from the National Federation of State High School Associations (2020a) gave the first specific recommendations for both bell cover material in multiple layers and an American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) rating of MERV-13. A very recent study using 16 woodwind and brass musicians from the Minnesota Orchestra (Abraham et al., 2021) also examined the spread of aerosols in wind instruments. In this study, Mellotone Acoustic Fabric (used commonly for speaker covers) and filter were used together. This study also concluded that one layer of filter was sufficient; multiple filter layers were shown to suppress the volume of a trumpet's overtones. If a mute or other object placed into the bell changes the pitch, does an object such as a bell cover or filter placed against the bell also change the pitch, and if so, can this change be perceived? In a study of six musicians researching perception of interval intonation, the subjects were unable to even distinguish whether intervals out of tune were either sharpened or flattened (Siegel & Siegel, 1977).

With the increasing use of bell covers and/or filters to reduce aerosol spread in rehearsals and performances involving wind instruments, this research focused on one aspect of performance, pitch (frequency). The intent of the experiment was to determine what effect, if any, bell covers and/or filters might have on the intonation (level of pitch) of wind instruments.

This study then sought to examine two primary issues:

1. Does pitch change when using both filter and bell cover?
2. Does pitch change when only using a bell cover?

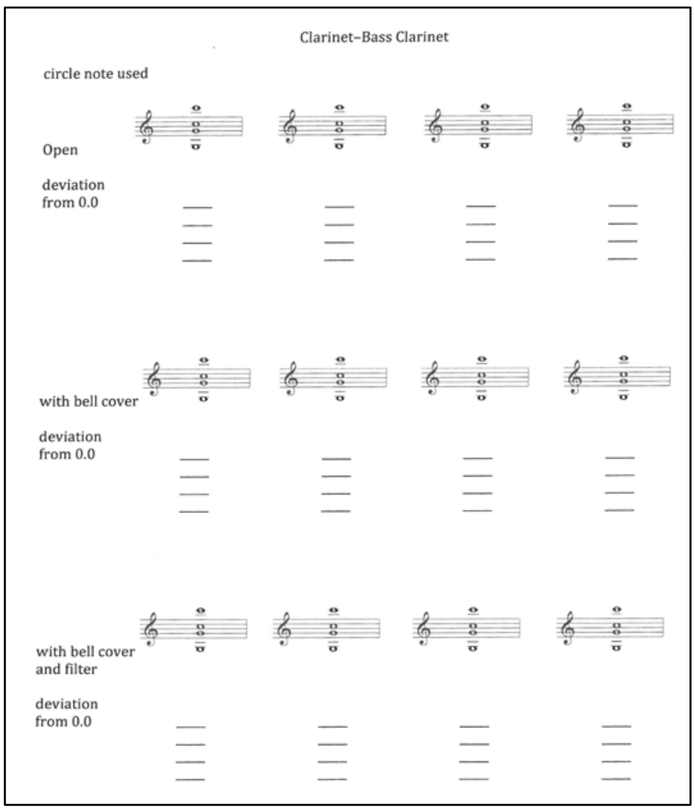
Method

First, we designed a data collection form (see Figure 1) for each wind instrumentalist in a large wind ensemble in the southwestern United States. The original data collection templates can be found at https://www.dropbox.com/s/77o9yi1ftkjbqs7/DataCollectionForms.pdf?dl=0.

Templates for flute, oboe, clarinets (B-flat[1], and bass), the saxophone family (alto, tenor, baritone), trumpet, horn, trombone, euphonium, and tuba were created (see Figure 1). The templates have the following in common: four pitches per instrument; at least one low, medium, and high pitch unique to each instrument's tessitura; and at least one "standard" tuning note in the four collected pitches. The 37 instrumentalists who participated in the study were: five flutes, one oboe, six B-flat clarinets, one bass clarinet, two alto saxophones, two tenor saxophones, two baritone saxophones, nine trumpets, three horns, three trombones, one euphonium, and two tubas. All were college students with at least six years playing experience; about 65% were music majors.

Figure 1

Sample Data Collection Form (Clarinet)



For this research, musicians were given both a bell cover and a filter. These bell covers were customized to fit each instrument. As advertised on the manufacturing company website, they were all black in color and made from 7-ounce fabric of 80% nylon and 20% spandex. Prior to the experiment, all musicians except flutes placed the bell covers on the instruments and reported no difficulty of fit. As an alternative to bell covers for flute, the school purchased transparent, plastic shields to be placed on the head joint of the flute. The filters used were cut from white, Merv-13 air filtration material, and were about 2mm in thickness. Although the filters were cut to fit the bell of each wind instrument, students of larger instruments reported considerable difficulty

[1] "B-flat clarinet" (also known as “B-flat soprano clarinet” or just "clarinet") in this study refers to the most common instrument of the clarinet family.

fitting them under the bell cover without the material collapsing into the bell. Before data collection, the instruments were inspected to ensure that cover and/or filter fit only along the external circumference of the bell. Collection of data took place in November 2020 in the university's instrumental rehearsal hall.

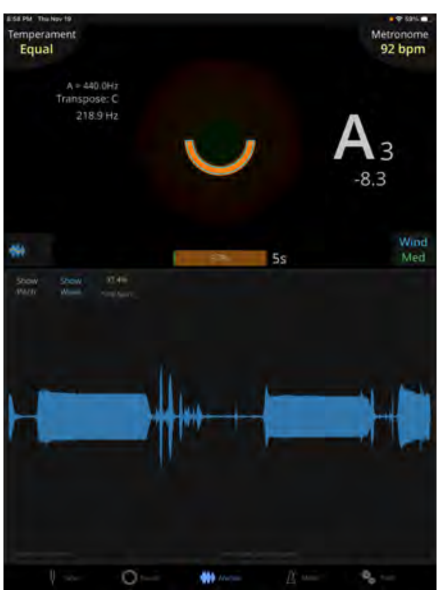
Before testing each instrument, each student was asked to play for about ten minutes. No attempt was made by the researchers to tune the instrument before testing. Musicians all sat six feet away from the recording source, a 10.5-inch iPad Pro running iOS software version 14.3. The iPad was placed such that only the researcher, and not the student, could see the screen. For pitch collection and measurement, we used the measurement app Tonal Energy Tuner (version 2.0.1) with the following settings:

- transpose: C
- A= 440.0 Hz
- equal temperament
- "wind" mode, "medium" in-tune range, and "slow" damping
- "tone meter sensitivity" set to 9.0
- pitches were collected in "analysis" mode (see Figure 2)

For this experiment, "in tune" referred to a pitch that is neither sharp (higher) nor flat (lower) than the standard Equal Temperament pitch for that note. Each time the musician performed a pitch, a reading was taken to measure the variance from "in tune." A note played perfectly in tune would be measured as "0 cents" or "0," meaning the note would be neither sharp nor flat. For a note sharp to the pitch, the amount of sharpness was measured in hundredths of a half-step ("cents"). A musician performing the note 10/100 half-steps sharp was recorded as "+10." A musician performing the note 10/100 half-steps flat was recorded as "-10." Three seconds after the start of each pitch performance, the intonation (tuning) of each pitch was recorded onto the data collection form. Each datum was entered to the nearest cent. A sample reading for baritone sax is shown in Figure 2. In this case, the datum for this pitch was recorded as "-8."

Figure 2

Sample Data Collection from Tonal Energy: Irregular Waveforms From Verbal Instruction



For each instrument, pitch/data collection began with the instrument performing "open," with no bell cover, air shield, or filter. Beginning with the lowest of the four reference pitches, each musician was asked to perform each of the four pitches from the data collection form for about five seconds, with no vibrato. This baseline collection then consisted of four iterations per note, for a total of 16 pitches. Next, each musician was asked to place the bell cover (air shield for flute) on the instrument. Using the manner described above, each musician played another set of 16 pitches for the same four notes, in the same order. Finally, both the filter and bell cover were applied to instruments, except flute and horn. Each musician then played a final set of 16 pitches. For the flute and horn, no filter was used, as we considered the use of filter for these instruments inherently inappropriate. For flute and horn, pitches for "instrument plus bell cover plus filter" were neither performed nor analyzed.

After the data collection for instruments, there were (except for flute and horn) a total of 48 pitches collected per person. For the flute and horn, 32 pitches were collected per person. Since there were four iterations of each pitch collected, the four iterations were averaged together to produce a mean pitch deviation for that note. Each musician therefore played four pitches—each four times for a total of 16 pitches played—with an intonation mean calculated for each "open" pitch. The musicians then played 16 pitches (each of the four pitches played four times) using bell cover/air shield with an intonation mean calculated. Finally, all musicians except flute and horn played 16 pitches (each of the pitches played four times) using bell cover and filter with an intonation mean calculated. In a few cases involving brass instruments in the lower register, the pitch was unsteady even after three seconds of performance. In these unusual instances, the datum was not collected; the student was told to wait a few seconds, take a slow, deep breath, and try again. The collected raw data can be viewed at
https://www.dropbox.com/s/ws0whnrts79amkw/ResearchData.xlsx?dl=0.

With only the exceptions detailed above (flute and horn), there were then three conditions under which each note was played by each musician, a note with no alterations made to the instrument that served as a baseline for comparison, and two experimental conditions: a note played with a bell cover on the instrument, and a note played with both a filter and a bell cover placed on the instrument.

In this study, the two primary questions were whether or not there was a measurable change in pitch due to bell cover and/or cover and filter together on each instrument. In the event of a negative answer to questions one and two, the analysis would end in a “nothing to see here, move along” type of conclusion. However, because of the possibility of a positive answer to question one and/or two, we considered two additional variables: the family of the instrument (brass or woodwind) and the note relative to the tessitura of the instrument (low, low-middle, high-middle, or high). Readers whose expertise lies in a more musical than statistical direction may benefit if the process of determining how these factors affect the pitch change is described in some detail. When statistically modeling two variables such as family and note as done in this study, additional questions must be examined. The third question to be examined in this study is then: 3) Is there an interaction between the effects of family (woodwind or brass) and note (low-to-high tessitura) on intonation?

Of course, this is a complicated question. For example, it might be the case that a brass musician experiences a large increase in pitch on the lower notes and a slight decrease in pitch on notes higher in the instrument's tessitura, while a woodwind player might note a slight increase in pitch on the lower notes and a large increase in pitch on the higher notes. Such models might be helpful for prediction but make succinct interpretation difficult. Any question of “What is the effect of family?'' must be immediately followed by a question of, “What is the effect for which note?" and vice-versa. If the answer to question three is negative, these "marginal" questions can be given meaningful answers without the need for follow-up, thus the final two research questions: 4) In the absence of interaction complicating interpretation, does the particular note being played by the musician have an effect on intonation? and 5) In the absence of interaction complicating interpretation, does the family (brass or woodwind) of the instrument being played by the musician have an effect on intonation?

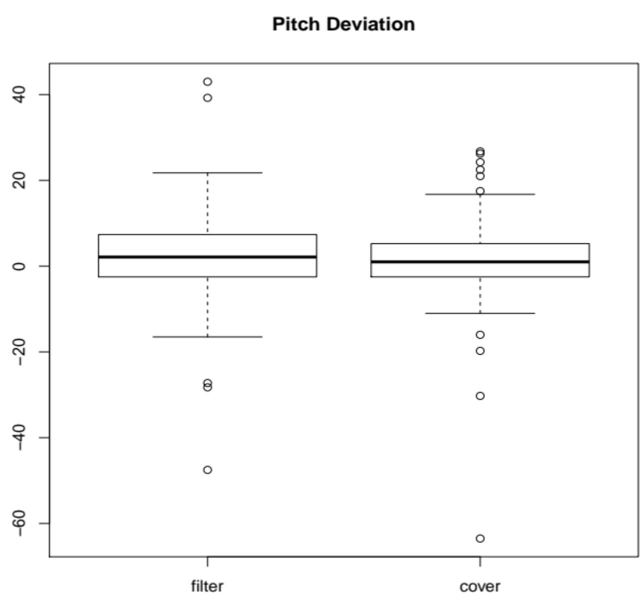
The data were assembled in a form that could be read by the “R” statistical program. R is a system for statistical computation, consisting of a language plus a run-time environment with graphic output, a debugger, access to certain statistical system functions, and the ability to run programs stored in script files (Hornik, 2017). The program was used to perform paired T-tests to address questions one and two, followed by F-tests from a two-way Analysis of Variance (ANOVA) model with interactions to address the rest of the questions. The purposes of the tests were to look for a significant non-zero mean difference between filtered and covered notes from the uncovered note and to determine if instrument family and the note played had an effect on any difference. The software package also produced graphics to accompany the linear models, some of which are shown here.

Results

We used a paired *t* test to answer questions number one and two. Figure 3 is a box-and-whisker plot analysis of pitch deviation for both filter and cover on the left side plot, and with cover only on the right, plotting for each instrumentalist the difference in pitch between the modified and unmodified (no cover, no filter) note. For both groups, a null hypothesis of a mean difference of zero (H_0: $\mu = 0$) was assumed, versus an alternative of a non-zero mean difference (H_a: $\mu \neq 0$).

Figure 3

Box-and-Whisker Plots of the Pitch Deviation (in Cents) in Both Conditions

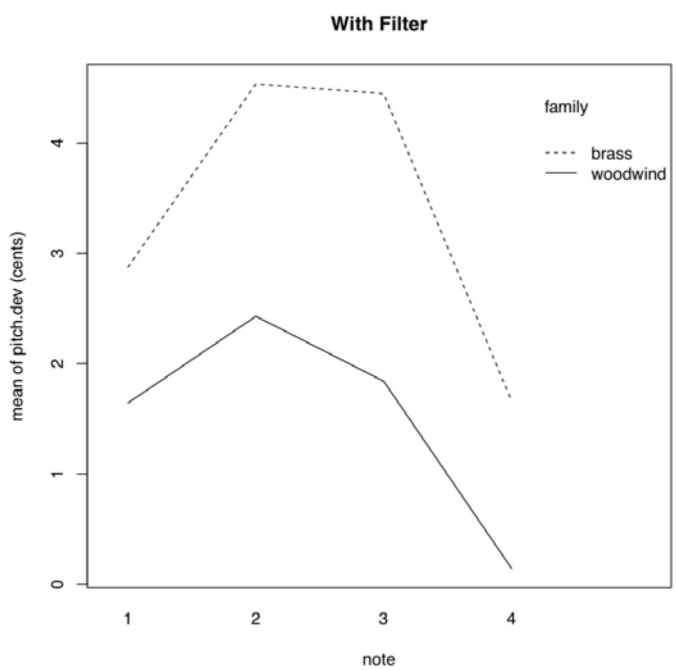


Musicians performing with a bell cover produced notes that were, on average, sharp 1.4 cents (SD=9.7) relative to the notes played on their unmodified instruments, though this difference was not statistically significant $t(143) = 1.72$, $p = 0.088$. A 95% confidence interval for the mean deviation in pitch for the cover alone was between 0.25 cents flat and 3 cents sharp. When performing with both a filter and bell cover, the notes were on average sharp 2.4 cents ($SD = 10.34$) relative to the notes played on unmodified instruments. This difference was significant, $t(111) = 2.50$, $p = .014$, even allowing for a Bonferroni adjusted cutoff of 0.025 due to multiple tests. A 95% confidence interval places this mean deviation between 0.25 and 4.00 cents sharp. The effect size here is small, $d = 0.23$, but given that the units here have physical meaning, they are interpreted later.

To answer questions three through five, there was an examination of the effects of family and note on pitch within only the filter/bell cover group of pitches, as this was the group in which was detected a difference. Recall that interpretation was complicated by the presence of any interaction between the effects of family and note on pitch. A trace of mean pitch deviation versus note played, by instrument family, is given in Figure 4, and suggests little evidence of any interaction.

Figure 4

Deviation of Pitch from the Mean by Note, Using Filter and Cover, Separated by Family



The data was analyzed using an Analysis of Variance, treating the note as an ordered factor, from low pitch to high pitch. Testing first for interaction, the computed result was $F(3, 104) = .024$, $p = .995$, leading to the conclusion for question three that there was no evidence of significant interaction between instrument family (brass or woodwind) and note (tessitura) on pitch.

In Figure 4, the brass family appears to have a sharper average deviation from uncovered pitch overall, and there is a higher average deviation from uncovered pitch on the two notes in the middle range of instrument tessitura versus the low and high note. Analysis of Variance again was used to test these differences for statistical significance. With regard to the note played, the computation of $F(3, 107) = .341$, gave a result of $p = 0.796$, concluding that the data indicated no reason to suspect that the higher average deviations observed in the middle of the instruments' tessituras was due to anything other than random chance. With regard to the instrument family, for the null hypothesis of no effect of instrument family on average deviation on pitch, the computation of $F(1, 107) = .895$, gave a result of $p = .346$. Again, the data indicated no reason to suspect any difference in mean pitch deviation between the brass and woodwind instrument families. Figures 5 and 6 give another look at the effect of note and family on pitch deviation.

Figure 5

Plot of Pitch Variability of all Instruments by Note, from Lowest Pitch to Highest Pitch

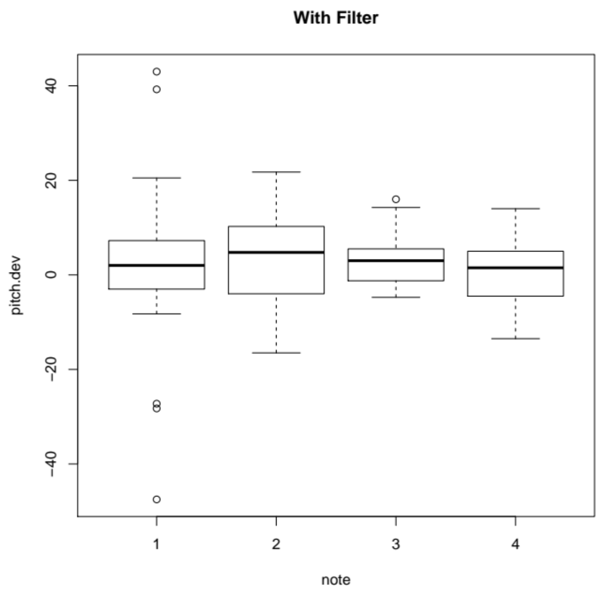


Figure 6

Box-and-Whisker Plot of Pitch Deviation from Mean, Using Cover With Filter, by Family

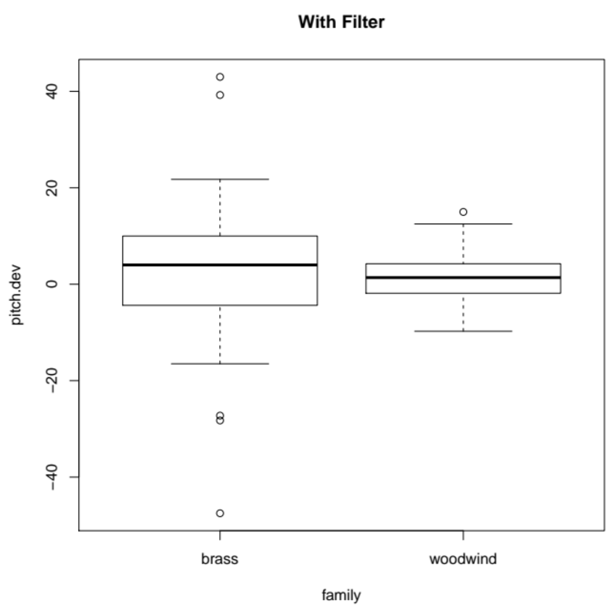
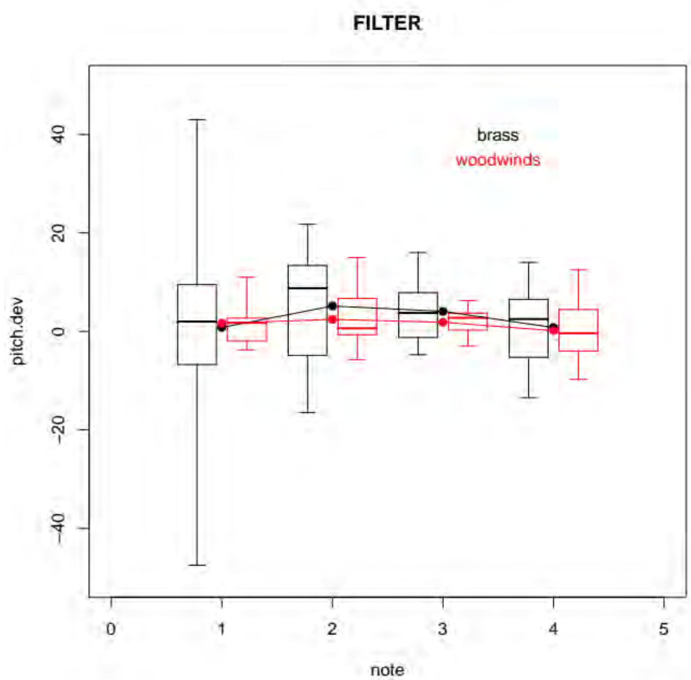


Figure 7, a version of Figure 4 with the raw data boxplots superimposed over the means, gives an indication that while the variability is perhaps higher in brass instruments in general, the variability is quite a bit larger when considering the lowest note in each instrument's tessitura. Bearing in mind that this extra variability might mask a small difference, the Analysis of Variance was recomputed, excluding the lowest note. The conclusion again was that there was neither a significant interaction between instrument family and note, $F(2, 70) = .05$, $p = .95$), nor a significant marginal effect of either instrument family, $F(1, 72) = 1.14$, $p = .29$, or note, $F(2, 72) = .988$, $p = .38$.

Figure 7

Box-and-Whisker Plot of Pitch Variance (in Cents) for Filter With Cover, Taking Into Account Both Ordered Pitch (Low to High) and Instrument Family



In summary, the use of both a cover and a filter made the mean pitch a little sharper. The use of bell cover alone caused a smaller variability in mean pitch, but was not consistent in either direction. The answers then to questions one and two are: yes, the mean pitch changed a little and no, the use of a cover alone had no significant effect. The answers to questions three, four, and five are: there was no significant difference on mean pitch intonation when looking at the role of family or tessitura. There was also no interaction between family and the note being played.

Discussion

This research suggested there is a slight tendency for the mean pitch to sharpen when using both a bell cover and filter. Will a listener perceive this level of sharpness? There is a considerable body of research already published regarding pitch discrimination, especially as to the ability of a musician to determine whether a pitch is sharp or flat. Some research has shown a tolerance for sharpness (Geringer & Sogin, 1988) that relates to these findings. If indeed the use of bell cover and filter has some inclination to sharpen the pitch of wind instruments, this change of intonation would be more tolerated by the ear. The register or octave of the instrument producing the pitch should also be considered. This research suggested a tendency for lower-pitched instruments to be more varied in pitch when using a bell cover and filter. There has been some research done already as to the ability of musicians to play in tune when a pitch stimulus is given by a higher-pitched instrument, compared to a lower-pitched instrument (Byo, Schlegel, & Clark, 2010). In that study, participants were asked to tune to a flute, oboe, clarinet, and tuba. The results of that study suggested participants were more likely to play out of tune when responding to the reference pitch from the tuba. In our study, when using both a filter and cover, the biggest pitch deviation sharp from an uncovered note came from the tuba; the biggest pitch change flat from an uncovered note came from the trombone. The implications of the compounding of error of improper tuning from an incorrect reference pitch are clear.

The next consideration was the amount of mean pitch deviation. In the findings of this research, when using both cover and filter, the mean pitch deviation was about 2/100 of a half-step sharpness, colloquially known as "two cents sharp." How well can a musician hear such a small difference in tuning? Regarding this topic, there is already extant research. In the areas of music perception or psyschophysics, the term used for the ability of at least half a population to hear a detectable difference in pitch is <u>just-noticeable difference</u>, abbreviated as "JND." The JND for frequencies below 500 Hz (below C5) is about 3 Hz and the JND for frequencies above 1000 Hz is approximately 0.6% of the frequency of the note (Kollmeier, Brand, & Meyer, 2008). We then compared two pitches from this study, one from a lower-pitched instrument and one from a higher-pitched instrument. For the tuba, we examined one of the pitches collected, B-flat2 (116.54 Hz), a common tuning note for bands. If the tuba were to perform this note two cents (2/100 of a semitone) sharp (the possible pitch mean variation with bell cover and filter shown in our research), would a listener be likely to hear the difference? A sharpness of two cents to this pitch would result in the tuba playing 116.68 Hz. This difference would certainly be far less than what would be perceived as JND. In this case, a JND of sharpness for the tuba performing B-flat2 would be 119.54 Hz. The two tubas in our sample played this particular note only 0.75 cents sharp and 1.25 cents flat (averaging 0.25 cents flat for this particular note) when playing with filter and cover, although it should be noted that across all notes the tubas played as much as 43 cents sharp and as much as 28.25 cents flat, suggesting that in practice there may be a substantial variation from the mean of -0.25 cents in this study.

Mean pitch deviation of an oboe performing a note in its upper tessitura, using bell cover and filter, was examined next. The note C6 (1046.50 Hz) for the oboe was the highest pitch collected with both a bell cover and filter (recall that in this study the flute did not use a filter). The difference between the frequencies of C6 and C-sharp6 is 62.23 Hz, and one cent difference in pitch from C6 to C-sharp6 is 0.6223 Hz. If the JND for this frequency is 0.6%, that would mean for a listener to perceive the C6 as "sharp," the C6 would have to be played at 1052.78 Hz, 6.28 Hz sharper than the standard C6 pitch. The JND of sharpness for C6 is then ten cents, but the average in this instance suggests that one would expect the oboe performing C6 with both bell cover and filter to be about three cents sharper, significantly less than the JND for this pitch. Again though, it should be noted that the variability of the actual pitch deviations observed around the average pitch deviation casts a shadow of doubt when considering only the average. The actual pitch deviation observed when an oboe played C6 with cover was 8.75 cents, only slightly lower than the JND of ten cents.

Planning for and compensating for a small mean pitch deviation of two to three cents in an ensemble setting may therefore be both unnecessary and impractical, given time constraints inherent in school rehearsal settings. Nevertheless, the actual pitch deviations that occur due to the inherent variance about that mean may veer into a range detectable by trained musicians, and cause noticeable issues for both musicians and listeners.

Recommendations

The most obvious limitation in this study was the small sample size. Would there be less, about the same, or more deviation with a population of, for example, over a hundred musicians sampled? What we hope to inspire from this research is a larger study involving several universities in diverse locations. As university setting in this study is a smaller Division 2 NCAA school, and the ensemble has in it both music and non-music majors, does the level of university have an effect on pitch mean, deviation from mean, or degree of intonation? Again, this is an unknown; we encourage other researchers to continue to examine these problems at different levels of higher education institutions. As we found a mean deviation of about two cents sharpness when using both bell cover and filter, one must evaluate how likely it is a listener could discern such a change. Since pitch discrimination varies by training and experience, this topic is appropriate for further research. A further recommendation arises from the huge variability in the performed pitch around the overall mean, particularly among the brass instruments in the lowest register. We recommend that for brass musicians with less experience, the lowest note in any future study be moved to a slightly higher pitch (for example, B-flat1). Because it seems likely that the Covid-19 pandemic will continue to affect instructional practice, the use of bell cover or cover with filter will probably continue to some degree. It is our hope that this research inspires other musicians and mathematicians to work collaboratively on the effects of these instrument modifications on pitch. Finally, as ten of the student musicians spontaneously opined that the tone quality was noticeably different when using both filter and cover, a related and important area of further research would be the effect on timbre of using an air filter and bell cover.

Keywords: music, Covid-19, filter, bell, cover, pitch, instrument, JND

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