

# Oral Cavity Movements of the Tongue During Large Interval Slurs in High-Level Horn Players

## A Descriptive Study

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**OBJECTIVE:** Recent publications describing lingual movement strategies within the oral cavity of brass players have established the existence of efficient and predictable movement patterns in healthy performers for a variety of performance tasks. In this study we extend the research to include the playing of large interval slurs in horn players. **METHODS:** Real-time MRI films at 40-msec resolution were simultaneously obtained in the sagittal and coronal planes in 9 professional horn players as they performed 2 repetitions each of 3 slur sequences spanning 1 octave, 1 octave + 3rd, and 1 octave + 5th at a *mezzo forte* dynamic level. Nine profile lines were overlaid on the images allowing the measurement of dorsal tongue edge movement using a customized MATLAB toolkit. Movement along lines representing the anterior, middle, and posterior oral cavity in the sagittal plane, as well as the vertical height of an air channel observed in the coronal plane, are reported. **RESULTS:** Both sagittal and coronal views demonstrate patterned tongue movements that narrow and widen the air channel during ascending and descending slurs, respectively. The magnitude of these movements is greater during larger intervals, though not perfectly consistent within each slur sequence. Additionally, the tongue position during notes tends to drift in the direction of the subsequent note in each sequence. We suggest that the observed movements may help to modulate air speed through the lips, possible attenuating embouchure muscle tension changes by assisting changes in lip vibration frequency. *Med Probl Perform Art* 2022;37(2):89–97.

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Video associated with this report is available on the journal website: <https://www.ingentaconnect.com/content/scimed/mppa> (see June 2022, supplementary material).

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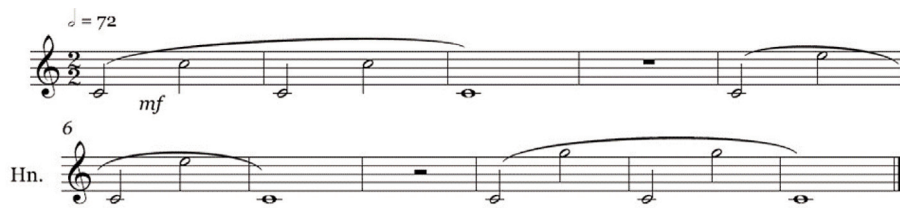
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**IN RECENT YEARS**, we have employed real-time magnetic resonance imaging (RT-MRI) in several studies of brass performers to examine changes in oral cavity configuration, particularly with respect to lingual movements. Comparisons between horn and trumpet players with and without embouchure dystonia have been made with respect to tongue stability during sustained notes.<sup>[1,2]</sup> In several other studies, motor activity of the tongue has been described in high-level horn players during the performance of multiple tonguing exercises,<sup>[3]</sup> ½ step trills,<sup>[4]</sup> as well as ascending and descending harmonic series.<sup>[5]</sup>

The information provided by these experiments has drawn increased attention among brass teachers and has led to the inclusion of RT-MRI images and films in the most recent edition of a popular horn method book.<sup>[6]</sup> Moreover, a research database of RT-MRI films studying a wide variety of exercises in horn, trumpet, and trombone players has recently been created through the MRI Brass Repository Project. This database (currently unpublished) is searchable by numerous criteria (e.g., instrument, embouchure health status, technical emphasis) and should provide many new insights for brass pedagogy as it gains usage.

Many aspects of oral motor control are yet to be examined in these films. One unanswered question has to do with lingual motor strategies involved in performing large interval slurs. To date, small intervals, as performed in ascending and descending harmonic sequences, have been studied revealing consistent patterns in high-level horn performers. Specifically, we have shown that in side views (sagittal views) of performers playing ascending harmonic sequences, there is a progressive anterior-superior movement of the tongue, creating a narrower passage for air flow on higher notes. Conversely, when playing descending harmonic series, the tongue tends to drop lower and is drawn backwards within the oral cavity.<sup>[5,7]</sup>

Performing intervals that include and exceed an octave has not previously been studied using RT-MRI. While it seems logical that similar airway narrowing during ascent and dilation during descent would be present, the extent to which this occurs is unknown. Further, the nature of the movements themselves has not yet been studied. For example, does the tongue move to a consistent position during



**FIGURE 1.** Large interval slur exercise consisting of 3 intervals, each with 2 upward and 2 downward slurs. Pitches are depicted as they appear for horn in E $\flat$ . Actual concert pitches are E $\flat$ 3–E $\flat$ 4 (first interval series), E $\flat$ 3–G4 (second interval series), and E $\flat$ 3–B $\flat$ 4 (third interval series).

ascent and descent on repeated large interval slurs? What is the extent of the movement, and is this reproducible?

Additionally, we published a study where we were able to concurrently view tongue movements from simultaneously obtained sagittal and coronal views,<sup>[8]</sup> a technique we refer to as simultaneous dual-plane imaging. We describe an air channel that forms between the dorsal tongue surface and the hard palate that is visible only in the coronal view, and we have noted how this channel becomes constricted on high notes and dilated on low notes. This phenomenon involves a three-dimensional shape change of the tongue itself, much like the shape change of the lips when whistling. Employing this dual-plane technique in the study of large intervals would provide valuable insight into the degree of coordination exhibited in these two planes of observation, providing a more complete understanding of tongue movement.

In an effort to address several of these questions, the current investigation used simultaneous dual-plane RT-MRI techniques to describe the movements of the tongue that are associated with performing repeated ascending and descending interval slurs of an octave or larger in high-level horn players.

## METHODS

### Subjects, Performance Device, and Testing Protocol

Nine professional-level horn players volunteered to participate in this study. Two were from the United States, and the remaining 7 were from Germany. All testing was conducted at the Biomedical NMR facility at the Max-Planck-Institute for Multidisciplinary Sciences in Göttingen, Germany. Prior to testing, the subjects gave written informed consent in accordance with the recommendations of the local ethics committee at the Max-Planck Institute in Göttingen, Germany.

The subjects performed on an MRI-compatible horn (pitched in key of E $\flat$ ) built by Richard Seraphinoff, Bloomington, Indiana. The horn consisted of a non-ferromagnetic bell flare connected by a length of brass tubing terminating in a leadpipe that was attached to a plastic mouthpiece. The instrument had no valves and required all note changes to be achieved by changes in embouchure

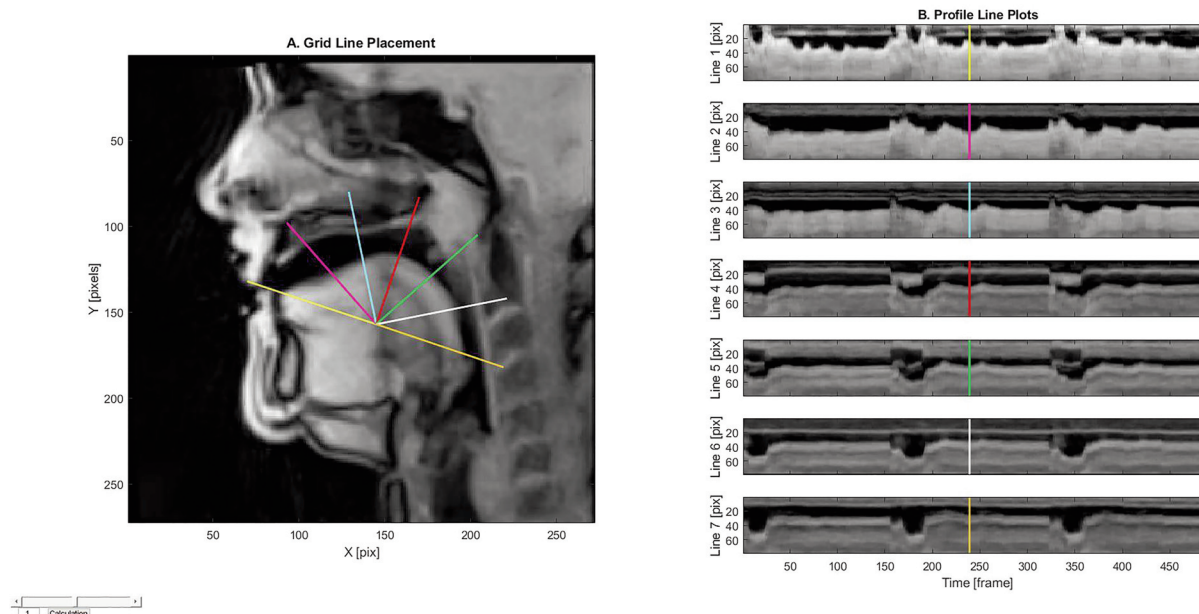
tension, flow rate, and oral cavity modifications. All musical exercises were performed in the supine position within the MRI magnet as described previously.<sup>[3,5,7]</sup>

A series of large interval slurs comprised the exercise under study and consisted of slurring up and down two times between E $\flat$ 3 to E $\flat$ 4, between E $\flat$ 3 and G4, and between E $\flat$ 3 and B $\flat$ 4 (see Figure 1).

To prepare the subjects, copies of the exercises were provided in advance of testing. Upon arrival at the testing facility, all subjects were allowed a warm-up period of 10-15 minutes to practice until they felt comfortable with the experimental instrument. Once inside the scanner in the supine position, subjects were also allowed to practice prior to MRI data acquisition. For testing, the subjects assumed the supine position inside the MRI magnet. The bell portion of the horn was secured outside the magnet at the feet of the subject, and the remaining brass tubing was extended caudally up into the scanner where the subject could hold it and the mouthpiece in the playing position. A fiber-optic microphone (Dual Channel-FOMRI, Optoacoustics, Or Yehuda, Israel) was positioned near the bell to record sound.

A PowerPoint presentation, operated by a technician from the scanner control room, regulated each trial. Following a keyboard stroke from the technician, a sequence of 3 slides was projected on a video screen in the scanner room and made visible to the performer by use of a mirror system mounted to the receiving head coil. Slide 1 provided a preview of the exercise manuscript. A second keyboard stroke from the test administrator actuated a second slide, again depicting the exercise, but with a “Get ready!” notation at the top. This slide remained visible for 5 seconds, and then progressed automatically to a third slide showing the exercise with the notation “Play after 4 visual beats!!” The appearance of this slide automatically generated an audio metronome signal from PowerPoint that was linked to both the scanner and a circular LED array in the scanner room next to the video monitor. Four signal flashes were seen by the subject at the performance tempo. The first of these metronomic signals triggered the scanner to begin acquisition, insuring that by the time the subject began playing on the 5th signal, data were being acquired. The flashes continued throughout the exercise to ensure temporal consistency between trials and subjects.

Communication between the subjects and the test administrator was possible by use of an intercom system



**FIGURE 2.** Profile line placement within the oral cavity (*panel A*) and resulting profile line graphs (*panel B*) in a representative subject. Profile lines 2, 3, and 6 were selected for study as representing the anterior, middle, and pharyngeal oral cavities. Plateau regions (see lines 4–7) represent periods of interval performance. The vertical lines in the profile line graphs are positioned just after the moment of the second iteration of Eb3 (frame 239) during the octave + 3rd interval.

between the control room and the scanner room. During actual testing, if an experimental trial was unsatisfactory to the subject, a repeat trial was allowed. The best performance was utilized for data analysis.

The precise methods and validation of RT-MRI have been previously published.<sup>[9–11]</sup> So, too has an explanation of the method for obtaining dual-slice real-time MRI images.<sup>[8,12]</sup> Briefly, the experiments were performed on a 3 T MRI system (Magnetom Prisma, Siemens Healthineers, Erlangen, Germany) with a maximum gradient strength of  $80 \text{ mT m}^{-1}$ . Data acquisition was accomplished with use of a 64-channel head coil. MRI measurements yielded an in-plane resolution of 1.4 mm, slice thicknesses of 8 mm, and a field-of-view of  $192 \times 192 \text{ mm}^2$ . Alternating sagittal and coronal image acquisitions at  $2 \times 25 \text{ fps}$  (20 ms/frame) were interleaved to produce the dual-slice images and were subsequently sequenced and synchronized to audio recordings of each performance to produce the dual-slice films.

### Data Analysis

For all analyses, the dual-slice films were divided into two separate films representing the two orientations (sagittal and coronal views), each synchronized to identical audio tracks. The detailed methods for obtaining quantitative data from these films are well-established,<sup>[2–5,7,8,13,14]</sup> as briefly summarized here. We utilized a custom MRI toolbox for MATLAB (MATLAB 2018a, Mathworks, Natick, MA, USA), including image processing and signal processing toolboxes. For sagittal views, a set of 7 grid lines was created at  $30^\circ$  angles from a hand-digitized baseline positioned

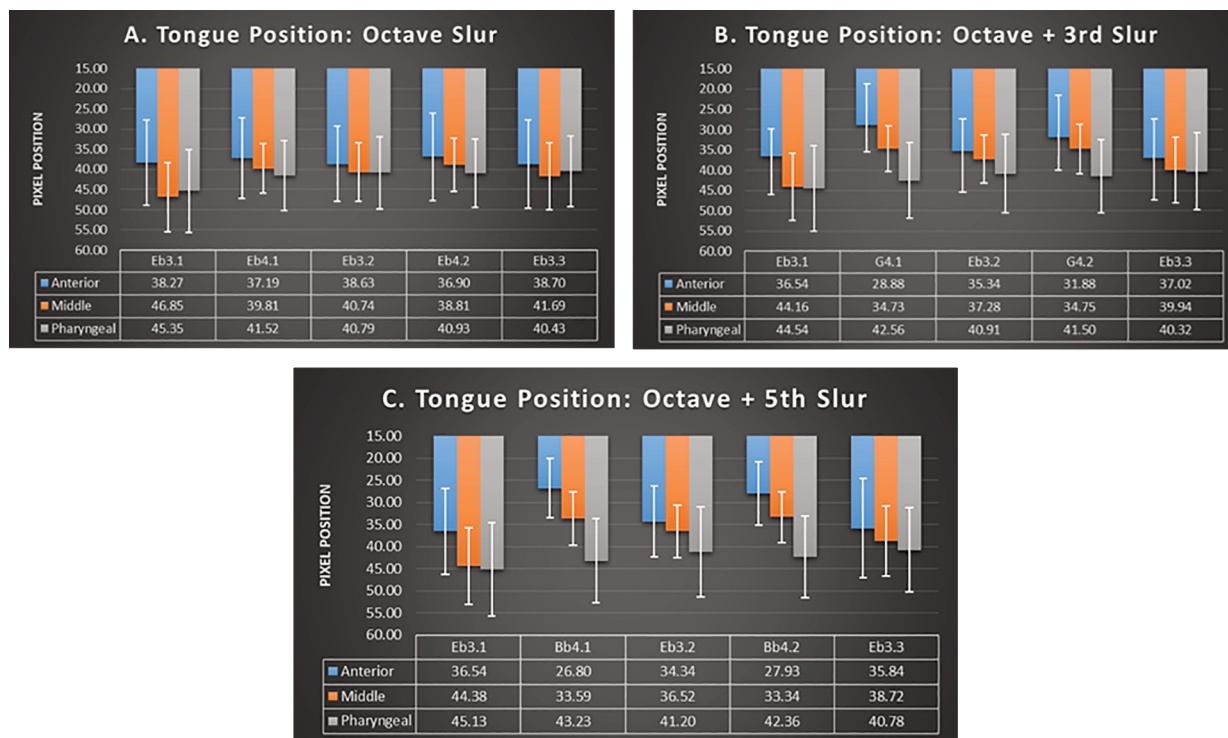
between the tip of the front incisor and the anterior-inferior edge of the 2nd intervertebral disc (see Figure 2A).

Temporal movements of the dorsal tongue edge along each of these profile lines were detected and processed using MATLAB to yield profile line graphs plotting tongue edge pixel positions (Y axis) as a function of time/frame number (see Figure 2B). Note that positions of the tongue along any profile line have larger values when the tongue is further away from the opposing surface and that upward and downward movements of the tongue are represented by decreasing and increasing pixel location values, respectively. Three of these profile lines were selected for quantitative analysis: Line 2 representing the anterior oral cavity, Line 3 representing the middle oral cavity (1/2 way along the hard palate), and Line 6 representing the pharyngeal region.

## RESULTS

### Movements of Tongue: Sagittal Views

Three general regions can be seen in Figure 2B and these are well depicted in the graph of profile line 6. Each of the sustained low points shown on line 6 (~pixel location 60) represents the pharyngeal region dilating for a preparatory breath before performing a slur sequence. Each plateau region on line 6 is coincident with the actual iterations of the slurs, plateaus 1, 2, and 3 representing the octave, octave + 3rd, and octave +5th slurs, respectively. These plateaus represent narrowing of the pharyngeal region. Looking at profile lines 2 and 3 during the same time peri-



**FIGURE 3.** Average tongue position across subjects (pixel means  $\pm$  SD) along each representative profile line (anterior, middle, pharyngeal oral regions) for the octave, octave + 3rd, and octave + 5th interval slurs.

ods, discernable movement patterns are seen, and these are described in greater detail later.

Tongue positions were tracked and quantified in each oral cavity region for each subject using the customized MATLAB toolbox, averaged across all subjects and subsequently plotted. As can be seen in Figures 3A–3C, for any 5 note series (A: octave, B: octave + 3rd, C: octave + 5th) a regular pattern exists for two of the three oral cavity regions. On the first Eb3 of each series, the tongue is positioned low in the oral cavity to create a larger space in all three regions. In the anterior and middle regions, the tongue then moves to reduce oral cavitation during the slur to the higher note, and on descending back to the next Eb3, moves back towards the original position. For example, compare the anterior cavity pixel positions of the tongue in Figure 4C from Eb3.1 to Bb4.1 and back to Eb3.2 (36.54  $\rightarrow$  26.80  $\rightarrow$  34.31). This pattern is repeated with subsequent notes. In contrast, tongue movements in the pharyngeal region are more random. This is more readily apparent in Figures 4A–4C, to be described later.

Figure 4 depicts the magnitude of movement of the tongue along each profile line in mm during each slur series of 5 notes. The initial data point (0 mm) represents the tongue starting position for the Eb3 that began each series. For each of the subsequent 4 notes identified in each slur series, the mean tongue position relative to the starting position of the tongue on Eb3.1 is plotted. For example, in Figure 4A, the first upward slur from Eb3.1 to Eb4.1 resulted in 0.76 mm of upward and forward movement of the tongue along profile line 2 (see Figure 2). On the next

slur from Eb4.1 back down to Eb3.2, the tongue moves down and back along the same profile line, settling in a position  $-0.25$  mm below the starting point on Eb3.1. With the exception of the pharyngeal region, the pattern is to move away from the starting position on Eb3.1 for ascending slurs, and to move back toward the original Eb3.1 position for descending slurs.

With respect to movement magnitude in the anterior and middle oral cavity regions, the trend is for more extensive movements during the larger interval slurs (compare pixel values between notes in Fig. 4A vs 4C). It also appears that for ascending intervals, the initial upward slur within a given interval series results in the largest amount of movement. Figures 4A–4C also illustrate that replicating tongue positions on identical notes within a given slur series is not precise. If the tongue assumed the same positions for each identical note in a series, then every Eb3 would be at the baseline (0 mm), and each of the higher notes in any series would have matching movement values. For the smallest interval, the octave slur, agreement between the same notes is fairly good in the anterior and middle regions, but in the larger interval slurs (Figures 4B and 4C), replication of positions on each note are less consistent.

Figure 5 presents a close-up view of the movement of the dorsal tongue edge along profile line 2 taken from the same representative subject shown in Figure 2. The undulating black line moving from left to right across the graph depicts tongue edge position during all three slur sequences. The beginnings and endings of each note sequence are depicted



**FIGURE 4.** Average tongue movement (mm) relative to the starting position on Eb3.1 during each slur interval in different regions of the oral cavity.

by vertical lines, and in the center of the graph, the epoch representing the octave + 3rd slur is identified by labels corresponding to different events in that sequence. In this segment, the tongue assumes its lowest position during the early moments of playing of Eb3, and it tends to drift upwards just prior to the playing of the G4 higher note, the start of which corresponds to the next vertical line. Once G4 is sounded, the tongue edge tends to descend during that note in apparent anticipation for the sounding of the next Eb3 commencing at the next vertical line. The pattern repeats itself in the second iteration of the slur. In cases where these vertical lines appear a bit blurred or even doubled, there was a very slight time lag between the precise ending of one note and the beginning of the next note.

At the beginning of each slur, there was a tendency for the tongue to “overshoot” its target position when ascending and descending. When the target note was achieved, the tongue edge tended to drift in the direction of the next note (see Figure 5 for each iteration of G4 and compare to each iteration of Eb3 in the octave + 3rd sequence that is labeled). The difference between the mean tongue edge position during each note and the maximum rise or fall of the tongue during ascending or descending intervals was identified as the overshoot. Figure 6 shows these values.

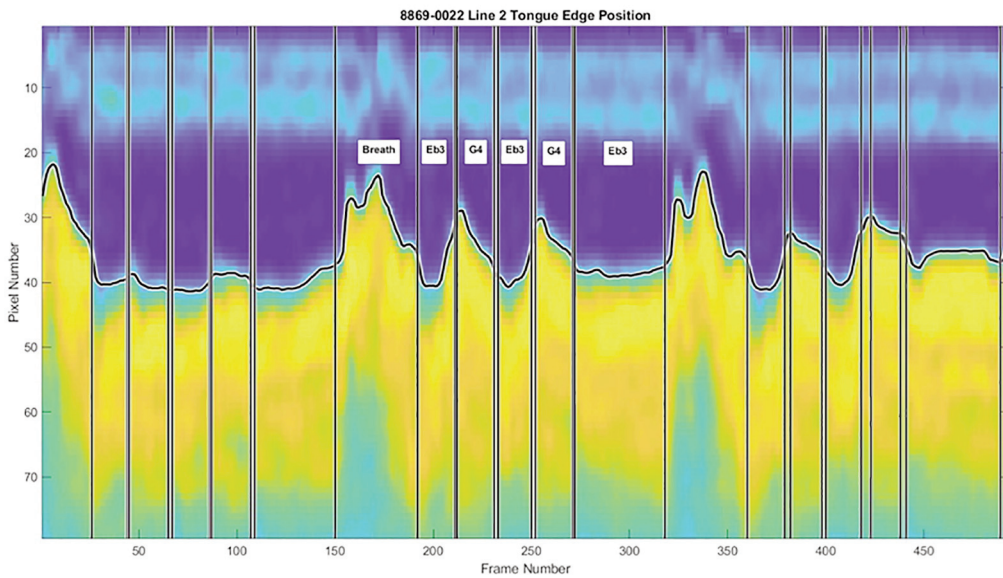
### Movements of the Tongue: Concurrent Coronal Views

Figure 7 illustrates dual-slice imaging of one of the performers during the octave + 3rd slur sequence at two different

moments in time (see video). In the left panel, large oral cavitation in both the sagittal and coronal views can be seen as the subject initiates the first Eb3 of the sequence. After the upward slur has been performed (right panel), the tongue position in the sagittal view has changed dramatically, as has the “channel” above the dorsal tongue surface in the coronal view.

To quantify the movements in the coronal plane, a single vertical profile line was positioned in the middle of the tongue, and movements along that line were recorded and plotted using the customized MATLAB toolbox (see Figure 8). As was the case in examining the profile line graphs derived from sagittal images, discernable patterns can be observed and will be subsequently explained.

To help understand patterns visible in the profile line graphs, Figure 9 shows an extreme close-up image. The central region of the exercise (the octave + 3rd slur) is featured and includes labels for the events occurring between vertical lines, analogous to what was presented previously in Figure 5. Two features are evident and similar to what was seen in the sagittal view analysis. First, the playing of any given note does not seem to correspond to a fixed tongue position. The first two iterations of Eb3 in the labeled sequence begin with the tongue edge quite low, with a rather steady drift upwards prior to playing the ensuing G4 iterations. When G4 first sounds, there appears to be an upward pulsing of the tongue that resolves back downward (most apparent in the second iteration of G4). This is similar to the overshoot described from the sagittal images. Similar patterns are apparent in the octave + 5th sequence as



**FIGURE 5.** Extreme close-up of dorsal tongue edge position along profile line 2 during large interval slurs in the example subject depicted in Figure 2. Central labeled portion comprises the octave + 3rd slur sequence (notes labeled accordingly). Regions to the left and right of this represent the octave and octave + 5th slur sequences, respectively. Vertical lines represent the start and stop of each note.

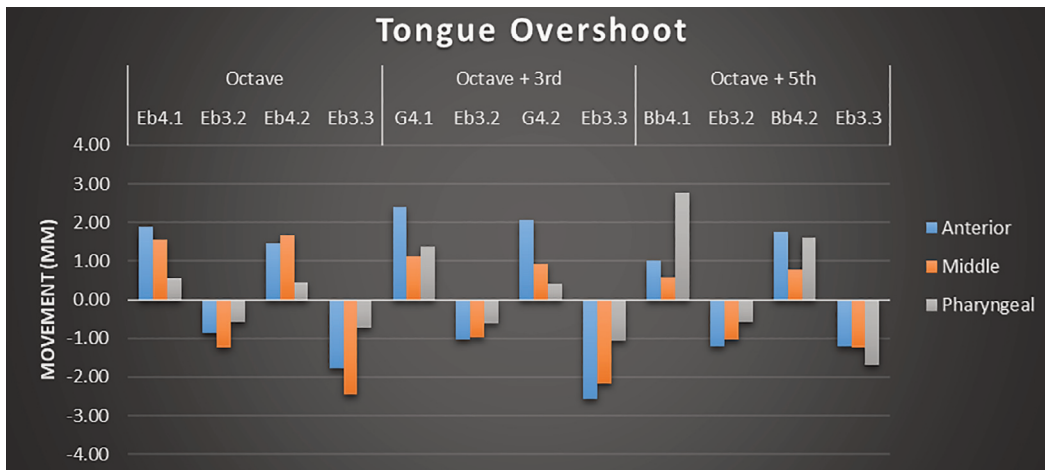
well (frames 358–490, events unlabeled), but are less obvious in the octave series (frames 26–149).

## DISCUSSION

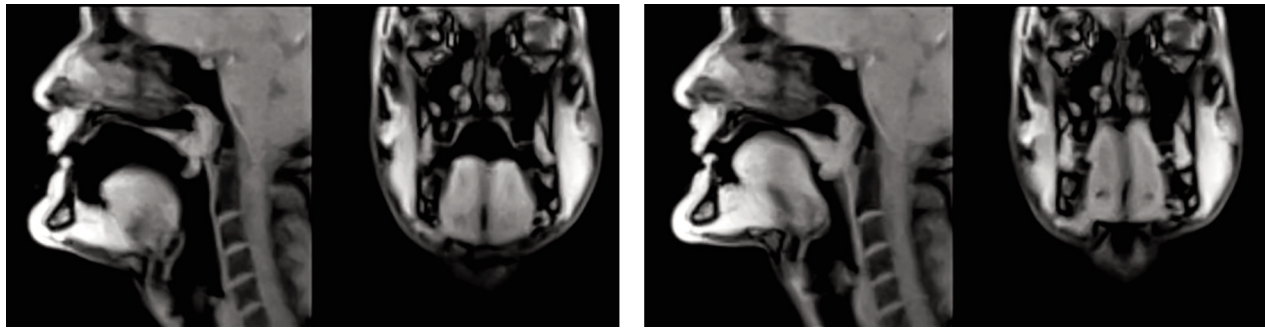
### Changes in Air Channel Diameter

This study confirms the existence of lingual movement patterns in the anterior and middle regions of the oral cavity during the performance of repeated ascending and descending large interval slurs. Specifically, the air channel formed between the dorsal tongue surface and its opposing

surface (the hard palate) narrows during ascending intervals and widens during descending intervals. This is demonstrated both in sagittal views and in coronal views depicting the air channel formed between the tongue and the hard palate (see Figure 7). Additionally, the magnitude of tongue movement is greater in both directions during larger interval slurs, and the location of the tongue on repetitions of individual notes is not precisely replicated (see Figures 4A–4C). Finally, there appears to be an overshoot of tongue position during note transitions as well as positional drift of the tongue in the direction of the next note in each slur sequence.



**FIGURE 6.** Average tongue movement overshoot (mm) during each slur interval in different regions of the oral cavity. Columns above the baseline indicate over-restricting the oral cavity, and columns below the baseline indicate over-dilating the oral cavity beyond the mean tongue position for each note.



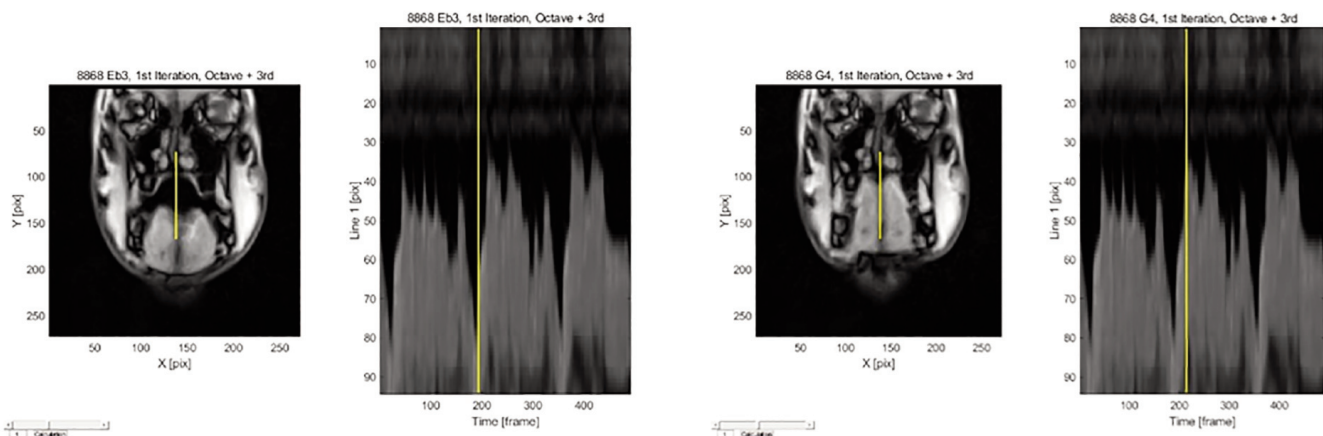
**FIGURE 7.** Concurrent dual-slice images extracted from the film of this exercise on a representative subject at the moment of the first iteration of Eb3 in the octave + 3rd series (*left panel*), and at the moment of the first iteration of G4 in the same sequence (*right panel*). (See associated video.)

### Air Channel Size, Pressure, Flow Velocity, and Changes in Pitch

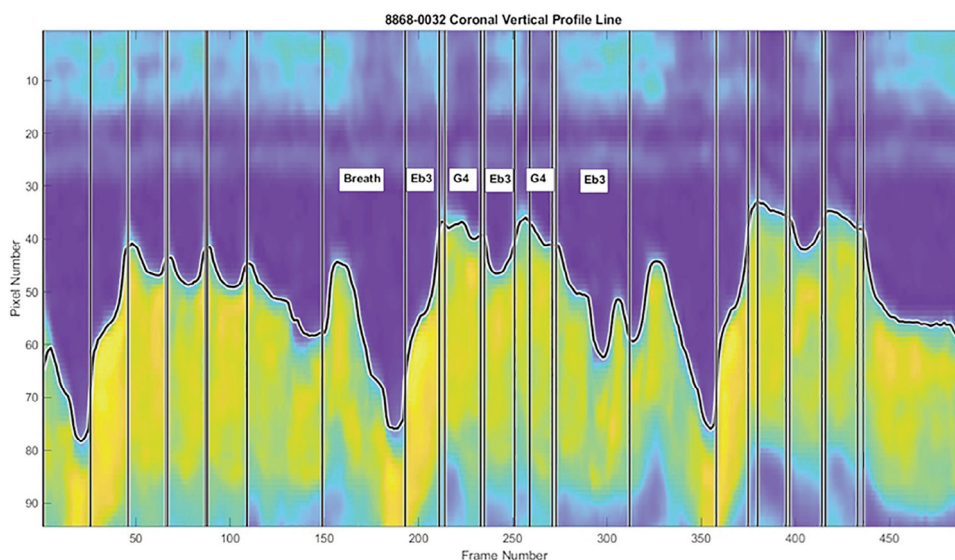
The sounding of a given note on a brass instrument involves oscillations between opening and closing of the lip channel at the requisite frequency. For example, using high-speed cinematography, Bromage et al. demonstrated that the frequency of lip vibration for a trombone player playing F4 was ~350 Hz, precisely the same as the acoustical frequency of that note.<sup>[15]</sup> The performance of repeated ascending and descending large interval slurs between changing notes thus requires the frequency of lip vibrations to increase and decrease rapidly and reliably. Numerous factors contribute to the regulation of oscillation frequency, and these have been thoroughly described in a recent book by Campbell et al.<sup>[16]</sup> Among these, changes in lip tension and aperture size are certainly important, requiring fine motor control of the facial muscles controlling the lips to alter the natural lip resonance frequency.<sup>[6,16–19]</sup> In addition, the pressure applied between the lips and the mouthpiece has been shown to vary, being

slightly higher on higher pitches than on low pitches.<sup>[20]</sup> However, these changes are not solely responsible for changes in pitch. The driving pressure of the breath as well as flow rates can also play a synergistic role by attenuating changes in muscle tension in the embouchure muscles as well as mouthpiece pressure.

The relationship of intra-oral pressure to flow and sound has been described by Fréour et al. from data collected on three trumpet players.<sup>[21]</sup> The subjects performed a series of notes ranging from Bb3 (233 Hz) to Bb5 (932) at three different dynamic levels (*pp*, *mf*, and *ff*). Their data indicate that intra-oral pressure increases with both pitch and loudness, and that flow (l/s) increases with pitch but tends to decrease with dynamic level at any given pitch. It was technically impossible to measure these two variables in the current investigation, but given that dynamic level was held constant, it may be postulated that changes in pitch were possibly due, in part, to changes in flow. Further, changes in pitch likely had commensurate changes in intra-oral pressure. Our RT-MRI images suggest a possible mechanism and rationale for these changes.



**FIGURE 8.** Coronal views showing the positioning of the vertical profile line at the tongue midpoint within the dorsal tongue “channel” and the resulting temporal profile line graph at two different points in time: at the initiation of Eb3 (left 2 images) and at the initiation of G4 (right 2 images). The edge of interest is best tracked between pixel locations 30 and 70 on the y-axis, and represents the dorsal tongue surface.



**FIGURE 9.** Extreme close-up of changes in the dorsal tongue position along the vertical profile line (coronal view) during large interval slurs in the example subject depicted in Figure 8. Central labeled portion comprises the octave + 3rd slur sequence (notes labeled accordingly). Regions to the left and right of this represent the octave and octave +5th slur sequences, respectively.

On the low note of each slur sequence, it may be suggested that intra-oral pressure was at its lowest. Slurring to the higher note in any series was accompanied by tongue movements that reduced the caliber of the air channel and possibly increased the intra-oral pressure. Further, the reduction in air channel diameter through the oral region would, according to the Venturi principle, increase the velocity of flow of the air column as it enters the lip aperture, contributing to a faster oscillation frequency (i.e., higher pitch). The converse would apply on descending slurs. The observation that larger changes in air channel diameter accompany larger intervals slurs is also consistent with this proposed mechanism.

### Variability in Movement Magnitude

First, it must be acknowledged that although the patterns of movement described in this paper seem rather clear, the location of the dorsal tongue edge across our 9 performers showed considerable variability (see Figures 3A–3C). Additionally, the magnitude of movement between adjacent notes in any slur sequence was not consistent in the pooled data (see Figures 4A–4C). Finally, the mean tongue position during any given note has been calculated from data that show marked drifting toward the mean position of the next note in any series (Figure 5). This drifting is also apparent when the dorsal tongue channel is depicted in the coronal view Figure 9.

A possible explanation for these observations may relate to the difficult nature of the exercise itself. Even at the relatively slow tempo of these repeated slur sequences (see Figure 1), the anticipation of needing to soon execute the next note may have caused some movements that would have been absent had a single slur been required.

Our previous work has shown relatively stable tongue positions during sustained notes,<sup>[2]</sup> and had we allowed more time on each of the 2 notes on a single slur rather than requiring multiple slurs, a more “settled” tongue position might have been achieved and the observed variability might have been avoided. Another possibility that deserves consideration is that though these were all professional level horn players, they may not all have been equally skilled at this rather difficult task. Although we allowed the performers to repeat trials, each trial consisted of the entire set of slur sequences performed consecutively. This was quite difficult, even for these advanced players, and missed notes did occur. Finally, although there is no other way to obtain the data we report, it must be noted that performing in the supine position within an MRI scanner presents a significant challenge for any brass player, and undoubtedly contributes to variability and inaccuracy. It may be interesting in the future to conduct fluoroscopy studies to see whether preserving a more normal, upright playing position would alter the current findings.

### Tongue Movement Overshoot

We observed what we have described as movement overshoot during these exercises (see Figure 6). Specifically, on each slur there was a marked maximal excursion point for the tongue edge relative to the mean position once a note was achieved. A possible reason for this during ascending slurs might be to create a momentary pulse of increased flow rate that assists the lips to increase the oscillation frequency. The reverse may be true for descending slurs as well, though both of these suggestions are purely hypothetical in the absence of actually measuring flow rate.



## Conclusions

The findings of patterned, dynamic movements within the oral cavity during large interval slurs in high-level horn players elucidates the physical phenomena associated with this performance task. It is tempting to take these results and try to make pedagogical recommendations. It must be noted, however, that the magnitude of the movements herein described is very small, ranging from less than 1 mm on the smallest slurs to no more than 7 mm on the largest slurs. To attempt to teach these subtle movements to a young musician seems unwarranted and may actually be distracting to the student. On the other hand, associating these movements with more concrete ideas has been done by numerous brass teachers. One of the more common ideas is to equate changes in pitch with the production of vowel sounds.<sup>[6,17]</sup> We have produced RT-MRI videos confirming the linkage between notes on the horn and vowel execution, and this phenomenon has been thoroughly incorporated into teaching.<sup>[6]</sup>

Further study substantiating these findings is clearly needed. We have previously tested elite professionals using RT-MRI, and it would be helpful to have data on the current exercises from additional performers of equal ability to see whether our observations are more clearly and consistently seen in these subjects. It would also be instructive to make comparisons between elite performers and intermediate-level performers. In terms of the specific exercises to study, it may be beneficial to examine large interval slurs individually rather than in a repeated sequence. While sequential repeated slurring is a critical skill for horn playing, isolating each slur in single trials would perhaps attenuate some of the variability observed in the current study. Finally, comparisons between different brass instruments would clarify the generalizability of our data.

**Authors Contributions:** PI is the principal investigator, responsible for study design, subject recruitment, data collection and analysis oversight, and manuscript preparation. JF and DV provided the expertise and technical assistance for all RT-MRI data collection and provided input into the prepared manuscript. DW and ST performed much of the technical data analysis and served as editors of the final manuscript. All authors reviewed and edited the final manuscript.

## REFERENCES

- Hellwig S, Iltis PW, Altenmüller E, et al. Tongue involvement in embouchure dystonia in trumpet players. Hochschule für Musik, Theater und Medien, Hannover, Germany, 2018.
- Iltis PW, Frahm J, Altenmüller E, et al. Tongue position variability during sustained notes in healthy vs. dystonic horn players using real-time MRI. *Med Probl Perform Art.* 2019; 34(1): 33–38. <https://doi.org/10.21091/mppa.2019.1007>
- Iltis PW, Frahm J, Voit D, et al. High-speed real-time magnetic resonance imaging of fast tongue movements in elite horn players. *Quant Imaging Med Surg.* 2015; 5(3): 374–81. <https://doi.org/10.3978/j.issn.2223-4292.2015.03.02>
- Iltis PW, Frahm J, Voit D, et al. Movements of the tongue during lip trills in horn players: real-time MRI insights. *Med Probl Perform Art.* 2017; 32(4): 209–214. <https://doi.org/10.21091/mppa.2017.4042>
- Iltis PW, Frahm J, Joseph A, et al. Divergent oral cavity motor strategies between healthy elite and dystonic horn players. *J Clin Mov Disord.* 2015; 2: 15. <https://doi.org/10.1186/s40734-015-0027-2>
- Epstein E. *Horn Playing from the Inside Out : A Method for All Brass Musicians.* Eli Epstein Productions; 2016: ix, 156 p.
- Iltis PW, et al. Inefficiencies in motor strategies of hornplayers with embouchure dystonia. *Med Probl Perform Art.* 2016; 31(2): 69–77. <https://doi.org/10.21091/mppa.2016.2014>
- Iltis PW, Heyne M, Frahm J, et al. Simultaneous dual-plane, real-time magnetic resonance imaging of oral cavity movements in advanced trombone players. *Quant Imaging Med Surg.* 2019; 9(6): 976–984. <https://doi.org/10.21037/qims.2019.05.14>
- Klosowski J, Frahm J. Image denoising for real-time MRI. *Magn Reson Med.* 2017; 77(3): 1340–1352. <https://doi.org/10.1002/mrm.26205>
- Roeloffs V, Voit D, Frahm J. Spoiling without additional gradients: Radial FLASH MRI with randomized radiofrequency phases. *Magn Reson Med.* 2016; 75(5): 2094–9. <https://doi.org/10.1002/mrm.25809>
- Uecker M, Zhang S, Voit D, et al. Real-time MRI at a resolution of 20 ms. *NMR Biomed.* 2010; 23(8): 986–94. <https://doi.org/10.1002/nbm.1585>
- Krohn S, et al. Multi-slice real-time MRI of temporomandibular joint dynamics. *Dentomaxillofac Radiol.* 2018; 48(1): 20180162. <https://doi.org/10.1259/dmfr.20180162>
- Iltis PW, et al. Movements of the glottis during horn performance: a pilot study. *Med Probl Perform Art.* 2017; 32(1): 33–39. <https://doi.org/10.21091/mppa.2017.1007>
- Iltis PW, et al. Real-time MRI comparisons of brass players: A methodological pilot study. *Hum Mov Sci.* 2015; 42: 132–45. <https://doi.org/10.1016/j.humov.2015.04.013>
- Bromage S, Campbell M, Gilbert J. Open areas of vibrating lips in trombone playing. *Acta Acust United Acust.* 2010; 96(4): 603–613. <https://doi.org/10.3813/AAA.918315>
- Campbell MJGAM. In: *The Scientist's Perspective on Brass Instrument Behavior in the Science of Brass Instruments.* Hartmann WM, ed. Springer, ASA Press: 2021: pp 31–58.
- Farkas P. *The Art of Brass Playing; a Treatise on the Formation and Use of the Brass player's Embouchure.* Bloomington, IN: Brass Publications; 1962: p65.
- Hill D. *Collected Thoughts on Teaching and Learning, Creativity, and Horn Performance.* Warner Brothers; 2000: p198.
- Rider W. *Real World Horn Playing,* 2nd ed. San Jose, CA: W. Rider Publ.; 2006: vi, 186 p.
- Petiot JF. Measurement of the force applied to the mouthpiece during brass instrument playing. Presented at Stockholm Musical Acoustics Conference SMAC03, Stockholm, Sweden, 2003.
- Fréour V, Caussé R, Cossette R. Simultaneous measurements of pressure, flow and sound during trumpet playing. Presented at 10eme Congres Francais d'Acoustique, Lyon, 2010.

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