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Visualization Techniques for Empirical Brass Instrument Research

By Matthias Heyne and Donald Derrick

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It is likely that every brass teacher has, at some point, wished that he or she could directly observe what goes on inside a student's mouth and throat. Unfortunately, the articulatory and/or sound-producing movements involved in brass playing are hidden from view inside the oral and pharyngeal cavities of the player. Yet, the exact nature of what is happening has long been the subject of intuition and comparison with other forms of human behavior. At least since 1584,[1] speech syllables have been used in brass teaching to guide students on what they should do with their articulators to produce desirable sounds.

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Given the historical desire to document the physical changes involved in brass playing, it is not surprising that X-ray imaging, or radiography as it was called in its early days, was applied to brass playing as soon as it became feasible. A number of dissertations were completed using various developmental stages of the technique, involving still frames and moving images until the discovery of the risks involved with X-ray exposure rendered further research too dangerous. Unfortunately, the demise of that technique also brought with it the end to a promising string of early empirical research, and its findings were, if not forgotten, at least never seriously considered by the brass playing community.[2] This article aims to change this situation by providing a summary of past research and encouraging brass players to make use of contemporary visualization techniques that have been used successfully either to capture directly or to infer from measurements the articulatory and/or sound-producing movements involved in brass playing.

X-Ray Studies (1954 – 1975)

The earliest study using X-ray imaging to investigate brass playing was Hall's 1954 PhD dissertation.[3] Although limited at the time to the capture of still frames, Hall's thesis stands out from all other X-ray studies due to the fact that Hall was the only researcher to control for variation introduced by different instruments and to make objective measurements with an early "sonograph" of the sound quality produced.[4] All of his participants played selected tones on a "control trumpet,"[5] in addition to their own instruments, and "sonograms" of the notes produced in all conditions were reprinted in the thesis. Unfortunately, the scan quality of the digitized document renders the extraction of his sonographic data impossible and restricts the readability of his X-ray findings to schematic tracings reproduced at small size. The main findings of Hall's study were that different participants used unique individual positions of the tongue and jaw while playing and that individuals tended to be consistent in using "the same basic formation in every register," indicating that modifications while changing registers "were not large."[6] All of Hall's tongue tracings were taken in the mid-sagittal plane (see Figure 1), and images taken during the spoken production of the extreme vowels "ah" (/ɑ/),[7] "oo" (/u/), and "ee" (/i/) (see Figure 2 for vowel positions discussed this article) in three different pitch ranges[8] allowed him to compare these tongue positions to the ones utilized while playing. The most "common formation" used during playing "was that of 'a' (ah)," but the author added, "Other players used the 'u' (oo) formation or intermediate formations between these extreme vowels."[9]

Figure 1. Image illustrating the orientation of the mid-sagittal plane

Subsequent studies by Meidt (1967),[11] Haynie (1969),[12] Amstutz (1970),[13] Frohrip (1972),[14] and DeYoung (1975)[15] largely confirmed Hall's findings, in addition to observing a wider range of playing condi-

Vowel positions discussed in the text

/i/ (“ee”), /ɑ/ (“ah”), & /u/ (“oo”) in American English (AE) (Hall, 1954)
/i~I/ (“Y” or “JÍ”), /a/ (“A”) in Czech (Šram & Svec, 2000)
/ʉ/ in Japanese (Kaburagi et al., 2011; Heyne & Derrick, 2015)
/ʉ/ (food) in New Zealand English (NZE) (Heyne & Derrick, 2015)
/u/ in Tongan (Heyne & Derrick, 2015)
/ʊ/ (foot) in NZE (Heyne & Derrick, 2015)
/oː/ (thought) in NZE (Heyne & Derrick, 2015)
/o/ in Japanese (Kaburagi et al., 2011)
/o/ in Tongan & Japanese (Heyne & Derrick, 2015)
/ə/ (lagoon) in NZE (Heyne & Derrick, 2015)
/ɐ/ in NZE (Heyne & Derrick, 2015)

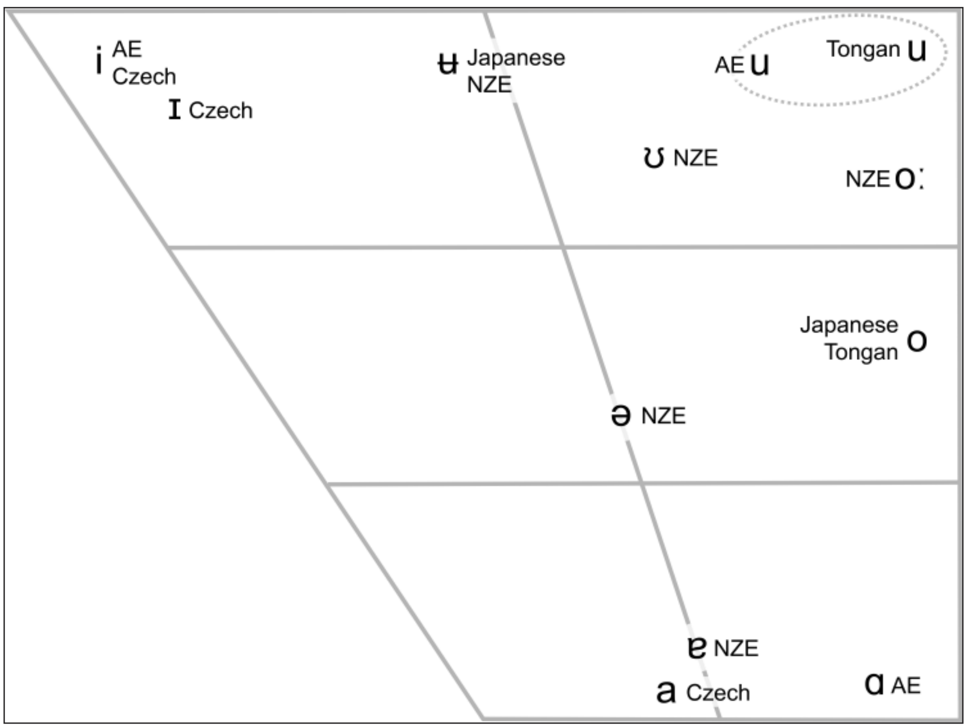

Figure 2. Vowel chart showing the placement of different vowels mentioned in the text[10]

tions, which included changes in dynamics and tongue placement for different types of articulations. Participants for some of these studies included players of various brass instruments, while Frohrip (1972) and DeYoung (1975) observed trombone players exclusively. With all the individual variation observed in these studies, it is not surprising that Meidt (1967) reported a difference in results compared to Hall’s (1954) findings with respect to register changes. Among Meidt’s participants, some players displayed large changes in tongue position with “the variations in formation … usually approaching, if not actually reaching, the extreme ‘ah’ and ‘ee’ vowel formations.”[16]

One other early study deserving of specific mention is Hiigel’s 1967 dissertation, *The relationship of syllables to pitch and tonguing in brass instrument playing.*[17] This researcher asked participants to think prescribed syllables printed underneath the music while performing selected notes and found no evidence “that thinking a syllable during performance will tend to simulate the tongue position resulting from the enunciation of that syllable.”[18] Similarly, significant differences were found “between the tongue placement for performance of the various pitches and styles and placement for the enunciation of the syllables” recorded separately, even for the players who claimed to use those specific syllables during playing. The overall tendency was for the “tongue arch” to be placed higher with the tongue tip “farther forward” in comparison with recitation.[19]

X-ray imaging was also used by Carter (1966)[20] to observe the role of the larynx during brass playing. He found that during brass playing, “the size of the glottis opening varies with loudness level, being small for soft playing and large for loud playing,” and that “there is no practical difference in glottis opening from the high to the low register, indicating that pitch control *within the normal playing register, can be discarded as a possible function of the variable glottis aperture* [italics in the original].”[21] Carter’s findings were partially supported by a study for the US Department of Health, Education, and Welfare (1971)[22] and initiated by Fay Hanson, which represents an early attempt at simultaneous measurement of various parameters involved in trumpet playing. They found the “control movements of the true vocal cord” to be “the most important mechanisms for the production of sound interruption in trumpet playing” with an opening “from 2 – 3 mm whenever a sound was produced.”[23] While these studies suggest conscious control of the vocal folds to regulate airflow—Carter made explicit reference to a theory put forward by Farkas[24]—later studies employing laryngoscopy have shown that changes in vocal fold position are rather small and moreover “self-adjusting or involuntary.”[25] It may be of further interest to brass players that a 1989 study by Mukai[26] found that professional players of wind instruments tend to keep their glottis almost totally closed or leaving only a small opening during playing—in contrast to amateur and beginning players, who kept the vocal cords open.[27] Bailey (1989) corroborated this finding, concluding from his data collected solely with trumpet players that, “While an observable distinction can be made between a relatively larger or smaller glottis during performance, there are no instances where glottal dimensions approach a fully abducted position similar to that observed during forced inhalation.”[28]

> “They found the ‘control movements of the true vocal cord’ to be ‘the most important mechanisms for the production of sound interruption in trumpet playing.’”

Finally, advances in X-ray technology have reduced the amount of radiation exposure so that modern technologies such as Cone Beam Computed Tomography (CBCT) can again be used to measure features of the vocal tract during sustained postures. Cilingir (2012)[29] applied this technique to measure teeth malocclusion and oral and nasal cavity size in order to investigate their effect on trumpet performance proficiency.

Observations of brass players' lips

The vibrating behavior of brass players' lips was first investigated by Martin (1942)[30] in his seminal study using a specifically designed L-shaped mouthpiece and stroboscopic photography with a resolution of 50 frames per second while observing cornet playing. Weast (1963)[31] expanded on Martin's findings by including players of all kinds of brass instruments, using an improved experiment design with transparent plastic mouthpieces and a stroboscope disc to observe the different phases of lip vibration. He found "overwhelming evidence of the upper lip being the primary vibrating mechanism,"[32] while "the activity of the lower lip was highly erratic."[33] Later studies[34] have shown the possibility of the reverse pattern occurring for upstream-type players,[35] and improved frame rates and image quality have enabled a more detailed description of brass players' lips. Most recently, researchers have used automated measurements of the lip opening area and pressure within the mouthpiece throat and at the instrument's bell to investigate the different mechanisms used to effect lip slurring on brass instruments.[36] Stroboscopic and kymographic[37] methods can also be employed to diagnose playing problems such as embouchure dystonia.[38]

"The most obvious application of MRI to brass research is real-time MRI, which allows the observation of the body in motion."

Lip vibration has also been studied with such indirect methods of observation as using a water nanometer to measure steady pressure in the player's mouth—compared with airflow velocity in the throat of the mouthpiece,[39]—or employing a strain gauge[40] to record lip movement in combination with a probe microphone to estimate sound pressure within the mouthpiece.[41] Recently, researchers have also adapted the principle of electroglottography, used to measure vocal fold vibration in speech research, to brass playing.[42] By placing two contact electrodes made of tin-plated copper foil on the upper and lower rim of a plastic mouthpiece and sending a high-frequency modulated current through the lips, the contact quotient of the lips can be calculated in a way that is far less intrusive than the direct-observation methods used in early studies. Finally, ecographs (ultrasonographic imaging of the lips at rest) can also be used to diagnose ruptures in the ring musculature of the embouchure.[43]

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Modern Visualization Techniques

Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging is the only modern visualization technique that surpasses the possibilities of X-ray imaging, though it does not image bone and teeth and has some other serious limitations. MRI scanners use very strong magnetic fields and radio waves to compute images of the human body, and no ferromagnetic materials can be taken inside the machine. This means that no real brass instruments can be played inside an MRI scanner—though this would also be problematic due to the small bore of the tunnel, which subjects have to enter to ensure that the body part being imaged is at the absolute center of the scanner. Another drawback of the MRI technique is the fact that the most powerful machines with the best resolution require subjects to be situated in supine position (lying horizontally), which inevitably would introduce small artifacts due to gravitational effects,[44] compared to the upright position normally assumed during brass playing. Additionally, loud repetitive noises inside the scanner arise from the need to switch on and off its magnetic coils rapidly, which could influence vocal and instrumental performance.[45]

While the potential exists to use functional MRI (fMRI) to look at brain activation specific to brass playing or shared with other forms of human behavior, such as speech production, the most obvious application of MRI to brass research is real-time MRI, which allows the observation of the body in motion. Recent advances in the way MRI composite images are computed has increased the temporal resolution of the technique to being able to produce an image every 20 to 30 milliseconds with a spatial resolution of 1.5 to 2 millimeters relative to the scanned plane.

Kaburagi et al. (2011)[46] used MRI to investigate the effect of a player's vocal tract on trumpet sound, requiring the player to maintain the same vocal tract configuration for at least 30 seconds. The instrument used was a plastic replica trumpet, built according to the specifications of a Yamaha student model (without any valves depressed) with an acrylic mouthpiece. In addition to detailed measurements of the vocal tract for three different pitches, the paper also includes images of the vocal tract while producing three different Japanese vowels. The comparison of tongue positions used during playing with those of the sustained vowels indicated that "the tongue posture for the low and mid pitches was similar to that for the back vowel /o/," while "the tongue posture for the high-pitch trumpet sound was similar to that for the vowel /u/, but it was located slightly posteriorly."[47]

A larger number of subjects playing different instruments were examined at the Freiburger Institut für Musikermedizin in Germany using real-time MRI. They produced a wonderful non-technical DVD-ROM with the title "Physiological Insights for Players of Wind Instruments," which features MRI videos explaining the tonguing and breathing movements involved in wind playing.[48] A more detailed study by Schumacher et al. (2013)[49] conducted at the same institution observed the motor functions in trumpet playing. The main findings of this research were:

1. With increasing tone pitch in octave jumps and in playing natural tones, there was an increase in total free space of both the oral and pharyngeal cavity. The increase of both to achieve the higher pitch was greater in the pharynx than in the oral cavity.
2. The increase in areas of oral cavity and pharynx are present also when switching from lower to higher loudness and when performing crescendo to decrescendo… However, no general difference in change of oral and pharyngeal cavity can be observed.[50]

The most recent research employing MRI for brass research is an ongoing project by American kinesiologist and horn player Peter Iltis in collaboration with researchers at the Max-Planck-Institut in Göttingen, Germany. For a study comparing oral cavity changes in performers of different brass instruments (trumpet, horn, trombone, and tuba),[51] they recorded one subject each performing an ascending pitch sequence over two octaves on a B.E.R.P. practice device, meant to simulate the aerodynamic resistance afforded by an actual brass instrument. The real-time image acquisition rate was 30 Hz, which allowed the analysis of double-tonguing, although no differences between the different instruments could be observed. In terms of the overall tongue movement patterns, however, an opposing pattern emerged for trumpet versus trombone and, to a smaller extent, for French horn versus tuba players. The results stated, "For the trumpet, the anterior area change … was characterized by a forward and upward projection of the tongue at both extremes of the register while for the trombone, a marked forward and upward shift of the tongue occurred when moving between the lowest … to [sic] the highest … notes."[52]

In another study,[53] the same research group recorded nineteen horn players, including ten elite players, using a custom-built, MRI-compatible horn that consisted of a non-ferromagnetic bell with graduated plastic tubing covering the distance from just outside the scanner to the player's mouth, which renders playing conditions more realistic than in previous MRI research. The recently published paper documents the successful acquisition of real-time video at 100 fps, offering great promise for further MRI research on the dynamics of brass articulation.

Ultrasound Imaging of the Tongue (UTI)

Ultrasound imaging of the tongue is a noninvasive and relatively inexpensive method of imaging the tongue with almost no known bio-effects.[54] It makes use of the same technology employed in hospitals to observe babies in utero and was first used to image human tongues in the 1980s.[55] An ultrasound probe, or transducer, is held against the skin underneath a person's chin so that its ultra-high-frequency sound waves can be channeled through soft tissues to the surface of the tongue, where they get reflected by the air boundary above it. The most common mode of imaging is the mid-sagittal plane (see Figure 1), although the technique can also be used to acquire coronal (side-ways) images of the tongue. See Figure 3 for a sample ultrasound image acquired during trombone playing.

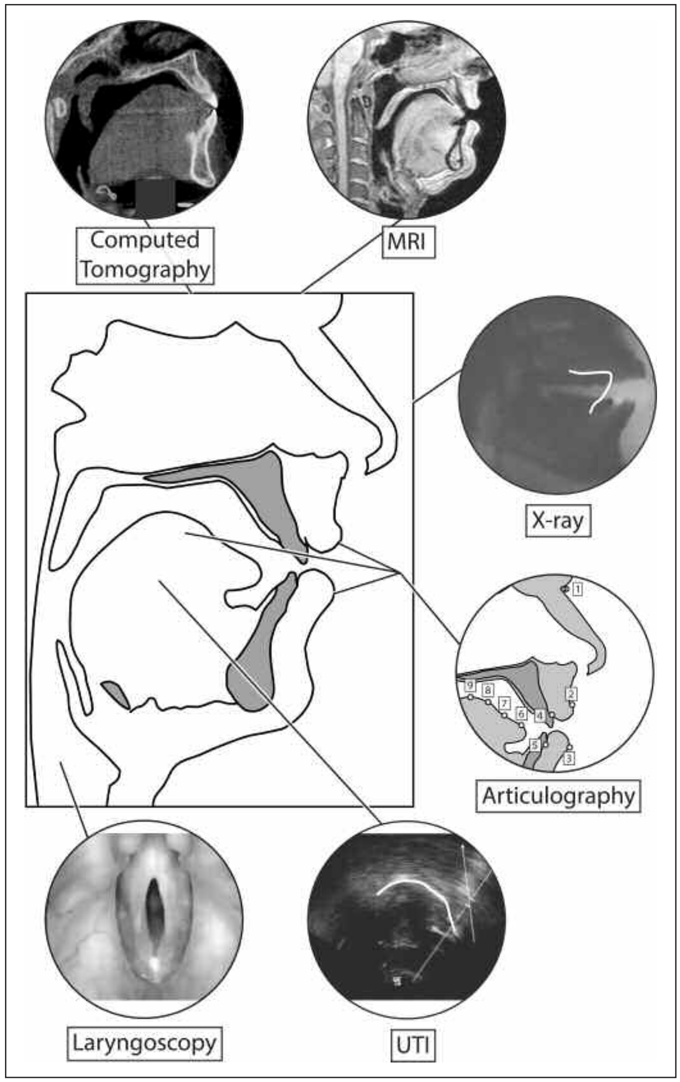

Figure 3. Visualization techniques mentioned in this article

The first application of UTI to wind playing, of which these authors are aware, was by Wein and colleagues (1989) at the Radiological Hospital in Prague with data analysis carried out in Aachen, Germany.[56] Regarding the use of the tongue during trumpet and tuba playing, a summary of their research on wind playing published in 2000[57] reports that the configuration of the speech organs for tones played in the middle and lower registers approaches a position similar to that when pronouncing the vowel "A" … The position of the articulators when playing in the upper register approaches, however, the position of the vowel articulation "Y" or "JÍ".[58] Later in the text they elaborate on this, stating that the articulation of sounds—vowels, consonants, and syllables—is only approximated and has individual variations on the interaction of the individual instruments and individual musicians.[59] Another important function of the tongue mentioned in this publication, but not reported in any of the earlier X-ray studies (possibly because it might be too obvious), is its use in helping to continuously moisten the lips, thus enabling their regular vibration. Lastly, the results of this study describe the vibrating tip of the tongue as a significant factor for sound production on brass instruments, especially the tuba, as well as the usage of rhythmic movements of the tongue base and the walls of the larynx to affect vibrato.[60]

Another application of UTI to brass playing was in a study by Zielke (2010)[61] at the university hospital in Düsseldorf, Germany. Tongue and motor activity of the neck and face were observed for players of different wind instruments, with the intent of quantifying and describing these behaviors for the purposes of music medicine. The author found that "tongue amplitudes" (meaning the displacement of the tongue during certain movements) were larger for players of brass instruments than flutists, for loud versus soft playing, and for attacked notes versus slurred articulation. Professor Angerstein, supervisor of Zielke's dissertation, is a phoniatrician and audiologist who runs a weekly consultation hour for wind players with tonguing issues, using UTI as a diagnostic and therapeutic tool.[62]

> "The author found that 'tongue amplitudes' were larger for players of brass instruments than flutists, for loud versus soft playing, and for attacked notes versus slurred articulation."

While we could find no information on how Wein et al. kept the ultrasound transducer in place underneath the participants' chins, Zielke reports that one of the investigators held the transducer under the chin of the participants while two other investigators performed the ultrasound and video recordings.[63] Although this might be sufficient for measurements of displacement, fixing the ultrasound transducer in place under the participant's chin becomes a necessity if different tongue positions are to be compared. This problem is related to the fact that ultrasound does not image any hard structures such as teeth or bones; therefore, there is no reference point on which to base measurements. Naturally, this impedes inter-subject comparisons, but head rotation must also be taken into account. Several solutions to this problem, such as motion tracking[64] and a helmet that rigidly fixes the transducer underneath the jaw,[65] have been explored, although both options do not seem to be particularly well suited for observing musicians without restricting their natural movements. To address this issue, we have adapted a non-metal jaw brace developed at our university to allow the application of ultrasound together with electromagnetic articulography (see the following section), which stabilizes the ultrasound probe against the jaw and thus ties probe motion to jaw motion.[66]

> "All participants assume a tongue position during sustained notes that at is at least loosely patterned on one of the vowels in their native language."

Our own research on the influence of native language on brass playing (observing trombonists exclusively) has confirmed many of the findings of the early X-ray applications.[67] With the exception of the most proficient trombonist[68] in our current sample of nine players, none of the participants changed their tongue position more than the difference between two closely placed vowels in their native language.[69] All participants, aside from the highly proficient player mentioned above, assume a tongue position during sustained notes that at is at least loosely patterned on one of the vowels in their native language. Furthermore, players who speak native languages that include a centralized vowel position such as schwa (/ə/) in English *lagoon* seem to have the option of using a tongue position close to that centralized vowel or a different one farther back in the mouth, as employed in the English words *thought* (/oː/), *food* (/u~ʉ/) or *foot* (/ʊ/).[70] Speakers of languages such as Japanese and Tongan that employ only five different vowels, however, do not seem to have the option of using a central position and can only assume the position farther back in the mouth during playing.[71] To watch ultrasound videos of trombone playing, see http://www.languageandmusic.info or Matthias Heyne's YouTube channel (search for "ultrasound trombone").

The latest high-speed ultrasound machines can record up to 121 frames per second, and three-dimensional ultrasound has recently seen its first application to tongue imaging.[72] At the same time, methods for head stabilization have improved,[73] and we have recently been able to collect ultrasound data concurrently with electromagnetic articulography.[74]

Electromagnetic Articulography (EMA)

Electromagnetic articulography uses alternating-current magnetic fields and electromagnetic detection to track the positions of small metal transceiver coils attached to the articulators (see Figure 3). Modern equipment can track the position of the sensors in three-dimensional space and can factor out head movement by attaching some of sensors to anatomical landmarks such as the mastoid processes. EMA offers excellent spatial (amount of detail) and temporal resolution (number of measurements per second), but can be sensitive to changes in temperature, air movement, and local magnetic fields. Additionally, applying the sensors is time consuming and invasive, and they may come loose during data collection.

The only documented application of this technique to brass playing thus far is Bertsch & Hoole (2014),[75] which was a pilot study with a single participant to demonstrate the usefulness of the technology for brass research. Interestingly, playing a regular brass trumpet did not seem to impair the magnetic field required for the data collection.[76] The mouthpiece used by the participant was a replica of his regular mouthpiece. We also just recorded a trombone player using a different EMA system[75] and synchronized UTI in our lab. Although we asked our participant to play a plastic trombone with a plastic mouthpiece for the main part of the experiment, at the end we switched to a brass trombone with a brass mouthpiece. Our preliminary analysis suggests that the brass had but a small impact, increasing the standard deviation of the residual recorded motion of the head motion tracking sensors by about 0.13 mm (from 0.43 to 0.56 mm) compared to that from the same piece played with the plastic trombone. Nevertheless, it is important to note that these sensors were located several centimeters away from the brass mouthpiece; metal may cause more variation in the tongue sensors, as they are closer to the brass.

Miscellaneous and Acoustic Analysis

In his PhD thesis on factors influencing sound generation on the trumpet, Bertsch included a study on trumpet warmup using thermal imaging.[78] Temperature changes were measured for selected areas of the face close to the attachment points of important facial muscles, and the main finding was that changes in blood circulation caused the measured temperatures to rise most significantly towards the middle of the face. This increase was correlated with playing proficiency; beginning players showed larger increases than more experienced players did.

“Advanced players seemed to rely more on the muscles surrounding the lips, while beginning players showed similar activation in the lips and surrounding musculature.”

Activation of facial muscles during brass playing has also been measured using electromyography, which detects the electrical potential generated by electrically or neurologically activated muscle cells. White (1972)[79] was among the first to apply this technology to brass playing[80] and found that muscle activity was higher for high vs. low and loud vs. soft playing. Additionally, he noted a few important differences between beginning and advanced trumpet players. He found that advanced players showed equal muscle activity between the upper and lower lips, while beginning players showed more activation in the upper lip. He also found that advanced players seemed to rely more on the muscles surrounding the lips, while beginning players showed similar activation in the lips and surrounding musculature. More recently, Iltis & Givens (2005)[81] and Kim et al. (2007)[82] applied this technique to study embouchure dystonia in a horn and tuba player, respectively.

Another interesting technique for indirect observation was used by Fréour as part of his PhD research.[83] In order to obtain detailed data on the respiratory processes involved in trombone playing, he used opto-electronic plethysmography (OEP), an optical tracking system with markers on the upper body to document rib cage expansion, and balloon-catheter systems with a gastric balloon to measure pleural (lung), gastric (stomach), and abdominal pressures.

“We have no illusions that scientific investigation is the only way to advance brass playing, and it should not be carried out for its own sake. On the contrary, we believe that making beautiful music should be the primary motivation for engaging in this kind of research.”

Finally, the acoustic signal produced during brass playing can, of course, also be used for scientific investigation. Researchers should be aware, however, of the multitude of factors that can influence brass instrument sound and keep them constant. These include the instrument (material, bore, mouthpiece shape), room acoustics, distance/angle to and transfer functions of microphones, less intuitive factors such as temperature and atmospheric pressure (which affect the speed of sound), and probably also the vocal tract morphology of individual players.[84] Several programs for audio analysis are available, some of which allow automation of measurements.[85]

Conclusion

This review of previous empirical research on brass playing using various visualization techniques shows that there are currently a number of promising techniques available to pedagogues and researchers who would like to base their teaching on empirical facts, rather than introspection. Although applying these techniques to brass research will, in most cases, require someone with specialist training to assist with data collection, we certainly believe that (based on our own experience) most institutions with access to such technology would be happy to cooperate with brass players who choose to engage in this kind of research.

This review also shows, however, that there is still a lot of research yet to be done; it is our hope that this article will encourage more people to do so. Not only do different studies suggest that there may be different mechanisms at work for different brass instruments (*e.g.,* regarding the tongue arch), but groups of players of different proficiency levels or even individuals might use opposing strategies to reach the same performance goals. Figuring out, for example, the relationship between the vibrating lips and the arching of the tongue (and adjustments in the pharyngeal cavity) would require the simultaneous observation of the lips and the employment of a technique such as UTI or MRI, all while a sufficiently large number of participants would have to perform on an identical instrument and mouthpiece.[86] We have thus refrained from providing any suggestions on how the findings from the cited research could be used to inform brass teaching, though there certainly may be some benefit of doing so on an individual basis.

Finally, we offer a short clarification to those readers who might be critical of an overly scientific approach to music making. We have no illusions that scientific investigation is the only way to advance brass playing, and it should not be carried out for its own sake. On the contrary, we believe that making beautiful music should be the primary motivation for engaging in this kind of research.

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Endnotes

1 Girolamo Dalla Casa, *Il vero modo di diminuir, con tutte le sorti di stromenti: Di fiato, & corda, & di voce humana* (Venice: Angelo Gardano, 1584). See also Edward H. Tarr and Bruce Dickey, *Articulation in early wind music: A source book with commentary* (Winterthur: Amadeus, 2007). Even earlier, Agricola (1545, but not in the first edition of 1529) included the syllables "dede" and "dirididride" in his general remarks about tonguing on wind instruments in Martinus Agricola, *Musica instrumētalis deudsch ynn welcher begriffen ist / wie man nach dem gesange auff mancherley Pfeiffen lernen sol / Auch wie auff die Orgel / Harffen / Lauten / Geigen / und allerley Instrument und Seytenspiel / nach der rechtgegründten Tabelthur sez abzusetzen* (Wittenberg: Rhaw, 1545), 33.

2 G. Irvine, "Spotlight on brass: Lessons learned (and ignored) from the past," *Canadian Winds: The Journal of the Canadian Band Association* 2, no. 1 (2003): 17 – 19.

3 J.C. Hall, "A radiographic, spectrographic, and photographic study of the non-labial physical changes which occur in the transition from middle to low and middle to high registers during trumpet performance" (Ph.D. diss., Indiana University, 1954).

4 This technique was previously applied by Gibson in his study, which was on acoustic data only. D.J. Gibson, "Recordings of differentiations in tone color produced by vowel sounds on the trumpet" (MA diss., University of Minnesota, 1942).

5 Hall, 267. This was a "Rafael Méndez model" with a "Méndez mouthpiece" manufactured by a "well-known manufacturer," not used habitually by any of the participants and "available locally."

6 Ibid., 246 – 247. "In nearly all cases, the changes were not as great as the changes between extreme vowels."

7 Note that Budde incorrectly states that the vowels produced by Hall's participants were sung; instead, Hall's dissertation reads, "with the instrument at his lips" each "subject said the following extreme vowels, prolonging each sound for three seconds to permit obtaining of the data" (p. 27). Also note that "ah" and "oo" were incorrectly transcribed as "A" and "O" in Zsaitsits's MA thesis, but were correctly transcribed as /ɑ/ as in American English "pod" and /u/ as in "booed" by Budde (p. 81). Paul J. Budde, "An analysis of methods for teaching middle school band students to articulate" (Ph.D. diss., University of Minnesota, 2011). Mario Zsaitsits, "Zur Zunge beim Spiel von Blechblasinstrumenten" (MA diss., Universität für Musik und darstellende Kunst Wien, 2012).

8 Hall, 27.

9 Ibid., 246 – 247.

10 Adapted from the chart of the International Phonetic Association, drawing on the following sources:

IPA Chart, http://tinyurl.com/itg1606c, available under a Creative Commons Attribution-Sharealike 3.0 Unported License. Copyright © 2005 International Phonetic Association.

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For Czech: Š. Šimáčková, V.J. Podlipský, and K. Chládková, "Czech spoken in Bohemia and Moravia," *Journal of the International Phonetic Association* 42, no. 2 (2012): 225 – 232.

For Japanese: A. Nogita, N. Yamane, and S. Bird. The Japanese unrounded back vowel /ɯ/ is, in fact, rounded central/front [ʉ-ʏ]. *Ultrafest VI* (Edinburgh, Scotland: Queen Margaret University, 2013); H. Okada, "Japanese," in *Handbook of the International Phonetic Association: A Guide to the Use of the International Phonetic Alphabet* (Cambridge: Cambridge University Press, 1999), 117 – 119.

For NZE: J. Hay, M. Maclagan, and E. Gordon, *New Zealand English* (Edinburgh: Edinburgh University Press, 2008).

For Tongan: M. Garellek and J. White, "Phonetics of Tongan stress," *Journal of the International Phonetic Association* 45, no. 1 (2015): 13 – 34.

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57 F. Šram and J.G. Svec, "Die Tonerzeugung beim Spielen von Blasinstrumenten. Sprache und Musik: Beiträge der 71. Jahrestagung der Deutsche Gesellschaft für Sprach- und Stimmheilkunde e.V. (Berlin: DGSS e.V., 2000). It is not clear from the text whether these findings are based exclusively on ultrasound research, as the authors also used X-ray imaging before switching to ultrasound. The publication also discusses findings gained by using videostroboscopy and videokymographie to observe the brass player's lips in motion (see endnote 36).

58 We believe that the pronunciations indicated by the use of Czech letters refer to the following vowel positions on the IPA chart (Figure 2): "A" = /a/, "Y" or "JÍ" = /i~I/. Cf. Š. Šimáčková, V.J. Podlipský, and K. Chládková, "Czech spoken in Bohemia and Moravia," *Journal of the International Phonetic Association* 42, no. 2 (2012): 225 – 232.

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62 More information is available on the website (http://tinyurl.com/itg1606d).

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66 D. Derrick, C.T. Best, and R. Fiasson, "Non-metallic ultrasound probe holder for co-collection and co-registration with EMA," in *Proceedings of the 18th International Congress of Phonetic Sciences* (Glasgow: ICPhS, 2015). This paper includes an assessment of the motion variance of the system, which showed that 95% confidence intervals of probe motion and rotation were well within acceptable parameters described in a widely-cited paper (Whalen et al., 2005).

67 M. Heyne and D. Derrick, "Trombone players seem to use different tongue positions while playing sustained notes, depending on their native languages," in *Proceedings of the 9th Triennial Conference of the European Society for the Cognitive Sciences of Music (ESCOM),* ed. J. Ginsborg, A. Lamont, and S. Bramley (Manchester: ESCOM, 2015), 446 – 455. M. Heyne and D. Derrick, "The influence of tongue position on trombone sound: A likely area of language influence," in *Proceedings of the 18th International Congress of Phonetic Sciences* (Glasgow: ICPhS, 2015). Matthias also presented about his research in the research room session of the 40th International Trumpet Guild Conference in Columbus, Ohio, in May 2015.

68 This participant could also be classified as a late bilingual, as he grew up in Mexico and subsequently migrated to the United States. He is thus very proficient in both variety of Spanish spoken in Mexico and American English.

69 *E.g.,* /ə/ vs. /ɐ/, /ʊ/ vs. /oː/ in New Zealand English (NZE).

70 Six of our seven NZE-speaking participants use a central position, while a single less-proficient player uses a position closer to the vowel in the word *thought* (/oː/).

71 The two Tongan and one Japanese participant in our current dataset all use this kind of tongue position while playing. For two of these players, this is very close to /o/, while for one player, it is closer to /u/.

72 S.M. Lulich, "Combined analysis of real-time three-dimensional tongue ultrasound and digitized three-dimensional palate impressions: Methods and findings," *Journal of the Acoustical Society of America* 136, no. 4 (September 2014).

73 See also: A.L. Miller and K.B. Finch, "Corrected high-frame rate anchored ultrasound with software alignment," *Journal of Speech, Language, and Hearing Research* 54, no. 2 (2011): 471 – 486.

74 See also: Derrick et al. (2015).

75 M. Bertsch and P. Hoole, "Tonguing on brass instruments: Highspeed visualization and benchmarks of fastest Tempi," in *Proceedings of the International Symposium on Musical Acoustics* (Le Mans: ISMA, 2014), 407 – 412. Video from the data collection is available on YouTube (http://tinyurl.com/itg1606de).

76 The system used in this study was a Carstens AG501 by Carstens Medizinelektronik, Bovenden, Germany.

77 Our system is a Northern Digital Inc. Wave machine.

78 M. Bertsch, *Studien zur Tonerzeugung auf der Trompete* (Vienna: University of Vienna, 1998). For a summary in English, see: M. Bertsch, "Variabilities in trumpet sounds," in *Proceedings of the International Symposium of Musical Acoustics*, ed. A. Myers (St Alban: Institute of Acoustics, 1997), 401 – 406.

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80 See also: C.L. Isley, "A theory of brasswind embouchure based upon facial anatomy, electromyographic kinesiology, and brasswind embouchure pedagogy" (Ph.D. diss., North Texas State University, 1972).

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82 J.-S. Kim and others, "Cooling can relieve the difficulty of playing the tuba in a patient with embouchure dystonia" [Letter to the editor], *Movement Disorders* 22, no. 15 (2007): 2291 – 2292.

83 Fréour.

84 See also: Bertsch (1998); S. Carral and M. Campbell, "The influence of the mouthpiece throat diameter on the perception of timbre of brass instruments," in *Proceedings of the International Symposium on Musical Acoustics* (Mexico City: Escuela Nacional de Música (UNAM), 2002), 233 – 245; P. Hoekje, "Comparing steady-state and transient phenomena in brass instruments," in *Proceedings of Meetings on Acoustics* 19, no. 1 (2013); R. Smith, "The effect of material in brass instruments: A review," *Proceedings of the Institute of Acoustics* 8, no. 1 (1986): 91 – 96.

85 *Praat,* frequently employed in speech research, is a free software application that allows scripting and works well

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for instrumental music. Researchers who would like more control of individual steps of the analysis can also use programming platforms such as MATLAB. P. Boersma and D. Weenink, *Praat: Doing phonetics by computer* [Computer software], available from http://www.praat.org. MathWorks, Inc. MATLAB [Computer software].

86 Note though, that a few studies have tried to observe multiple factors at the same time, including Nichols et al. (1971), Logie et al. (2010) and Fréour & Scavone (2011).

87 B. Gick, I. Wilson, and D. Derrick, *Articulatory phonetics* (Chichester: John Wiley & Sons, 2012).