More Air, Less Air, What is Air?

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Playing a brass instrument involves the engagement of several physiological systems while striving to respond to multiple layers of musical goals. Perhaps this is why discussions on brass pedagogy have failed to produce a consensus. Perspectives on how best to reach these musical goals or to teach someone else to achieve them most likely reflect differences in personal experience, individual differences in awareness of airflow or muscular tension, or the extent to which their instructors have focused attention on various aspects of their individual performance goals. Students who achieve success do so frequently via perseverance, rather then efficient teaching strategies. The strategies brass players employ to control the physiological systems that are required to enable or improve performance have yet to be satisfactorily identified and their effects have not been measured during musical performances and across the brass family. So, the questions that need to be entertained are whether or not there are indeed multiple strategies to success, how that success is ultimately measured, and what, if any, are the common denominators and/or significant differences among the successful strategies. These questions cannot be answered until the physical constraints of each brass instrument have been measured. Before one can discuss whether managing embouchure pressure or the sensation of airflow, etc. alters performance, we must understand what the requirements for air support and embouchure tension are as a function of instrument, pitch, loudness, and timbre.

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Resistance to airflow in the embouchure resonated by a brass instrument produces the sound we recognize as the brass sound. Defining the role of air during brass performance requires describing how changes in air support (measured as air pressure in the mouth, behind the embouchure, hereafter referred to as intra-oral pressure) and airflow through the instrument vary as a function of pitch and loudness. Measures of intra-oral pressure and airflow can be used to draw inferences about the resistance of the embouchure to air and the relative size of area of the embouchure that allows air to flow.

Several studies have measured airflow and intra-oral pressure during trumpet performance. Bouhuys measured airflow and changes in lung volume during performance on the bugle, trombone, flute, clarinet, oboe, and recorder. Bouhuys reports that airflow is stable at a given pitch and loudness, that intra-oral air pressure requirements increase with pitch while airflow decreases with ascending pitch. He also notes differences in the required intra-oral air pressure needed to produce tones as a function of the instrument. Fletcher and Tarnopolsky (1999) studied the intra-oral air pressure generated by three experienced trumpet players, one who played professionally. They observed that individual performers varied in the amount of intra-oral air pressure they could generate. They found that increasing intra-oral air pressure while playing a single pitch increased loudness (dB), thus altering the extent to which the instrument's bell radiated energy. This increase in energy radiating from the bell was accompanied by more brightness in the sound measurable by the increased amplitude in higher harmonics found in the sound spectrum. Further, they found that each given pitch required a minimum level of intra-oral air pressure to initiate the note (minimum onset pressure) and had a maximum air pressure level beyond which the pitch could not be maintained.

Of all of the studies that have been done on brass performance, none has been more significant for brass players than the observations made by Arnold Jacobs, the former principal tubist with the Chicago Symphony Orchestra. Due to his reputation as an excellent performer, fellow brass players took Jacobs's statements more seriously than those that were delivered by the scientific community. Jacobs was able to utilize his findings to help generate and support a methodology that later became known as "Song & Wind" (Fredericksen, 1996). A summary of this method asks brass players to focus their cognitive energies on the steady and relatively unforced release of the air coupled with due attention on the music being made. If this summary appears to be an oversimplification, it is certainly not meant to be. Nothing about brass playing can truly be explained in single sentence, much less the brilliant lifetime observations of an incredible musician such as Arnold Jacobs. It does, however, enable us to place Arnold Jacobs's methodology into a camp of brass pedagogy that, for lack of a better description, is more air-centered rather than embouchure oriented. Jacobs believed that focusing on *Song and Wind* would more naturally pull the other systems, such as embouchure, support, etc., into balance without focusing on them specifically with the aid of the conscious mind. What actually were the results of Jacobs's experiments? Jacobs conducted research in 1959 and 1960 with the assistance of Benjamin Burrows who was then at the University of Chicago's Billings Hospital (Fredericksen, 1996, p. 120). The results of this research were never published. Only anecdotal comments made by Jacobs in subsequent interviews and masterclasses remain. In short, Jacobs claimed that intra-oral air pressure increases as players ascend in pitch and that airflow in the horn consequently decreases. Jacobs went further to claim that intra-oral pressure and airflow were consistent at a given enharmonic pitch and dB level, regardless of the instrument being played. According to Jacobs, a tuba player and a trumpet player create the same amounts of intra-oral pressure and airflow in their respective instruments when performing the same enharmonic pitch. Jacobs's equipment recorded maximum levels of intra-

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oral pressure and airflow during the production of any one tone. The first goal of our study is to replicate Jacobs's unpublished research and extend it by also measuring changes dynamically rather than recording only peak measurements. This will provide a more consistent and common language to work with when discussing the role of air in playing a brass instrument. It will also help to clarify the differences of perception that brass performers experience not only on an individual basis but across the family of brass instruments as well.

"Any given pitch on a brass instrument has to generate a minimum amount of intra-oral air pressure before a tone is commenced."

Eleven musicians (three on trumpet, two on horn, four on trombone, and two on tuba) performed musical exercises using the same pitches (within instrument range), selected to allow comparison of air support systems as a function of pitch, loudness, and articulation. Airflow in the horn was measured in liters per second (lps) by using an airflow sensor (PTL-1) and amplifier (MS-IF2) produced by Glottal Enterprises. The sensor was attached to the end of the bell of each instrument. Intra-oral air pressure was measured using a fine (external diameter < 1.6 mm) Tygon microbore surgical plastic tube attached to gas pressure sensor produced by Vernier Software & Technology (GPS-BTA). Sound was recorded using a microphone placed approximately one meter from the bell of each performer's instrument. Airflow, intra-oral pressure, and sound were sampled at 11,000 HZ using LABVIEW (National Instruments) software and Coulbourn's Lablinc V hardware. In addition to measuring intra-oral air pressure, airflow in the instrument and decibel level (from here on labeled as sound pressure level or SPL), a variety of other measurements were also taken including mouthpiece force on the lips, muscular tension in various parts of the body, video analysis, etc. For the purposes of this article, however, only the data directly related to the role of air in brass playing will be discussed.

Perhaps the most discussed of the three measurements is the role that intra-oral air pressure plays in playing a brass instrument. Intra-oral air pressure increases with both SPL and pitch, but by how much? For example, what is the difference between the intra-oral air pressure generated by a tuba and a trumpet player? Any given pitch on a brass instrument has to generate a minimum amount of intra-oral air pressure before a tone is commenced. This minimum amount is referred to as the onset pressure (Fletcher & Tarnopolsky, p. 875). Figure 1 displays the airflow level, the SPL, and the onset pressure for three notes D2, D3, & D4 played on the trombone up to roughly the same dynamic marking. The horizontal axis covers three seconds with onset and crescendo. The first of the three graphs displays airflow on the left axis (liters/sec). The second graph, stacked immediately below the first one, displays the SPL. The third and bottom graph displays intra-oral air pressure (measured in kPa on the left of the graph and psi on the right). Each intra-oral air pressure reported here is the additional pressure above the ambient atmospheric pressure.[1] There are several things of interest to point out in this figure. First, the airflow level is in inverse relationship to the intra-oral air pressure. The highest note, D4, produces the lowest airflow but requires the highest intra-oral pressure. The opposite is true for the lowest pitch, D2, while the intermediate pitch, D3, falls in between. The finding that there is an increase in intra-oral air pressure (if the SPL level is also maintained) and a consequent decrease in airflow through the horn as register increases was found across each of the instruments we studied. Perhaps of more interest is the onset pressure for the three notes. Observe that, although all three of the graphs start rising at the same time, the airflow and especially the pressure reach stable values slightly before the SPL. That is, pressure and resulting airflow are established approximately five one hundreds of a second before the performer releases the note.

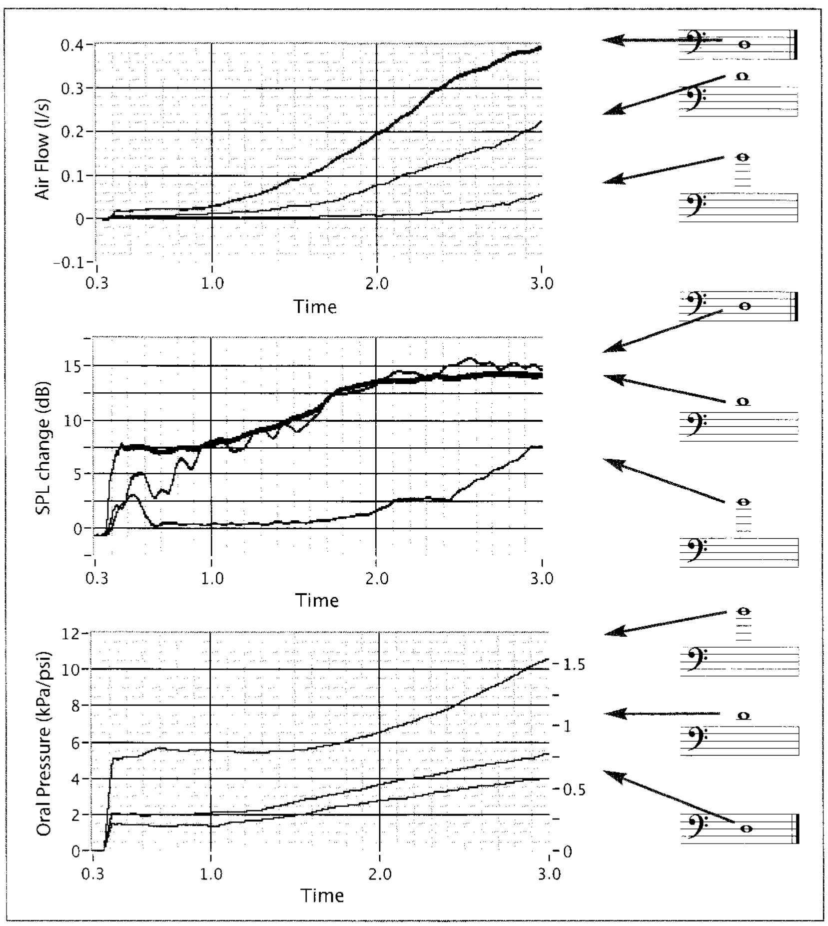

Figure 1: Airflow, SPL & intra-oral air pressure on three octaves of D on the trombone during a crescendo.

In Figure 2 we also see realizations of airflow, SPL, and intra-oral air pressure. This time, however, they are as a result of an ascending arpeggio. The first set of three graphs on the left displays a performance by a professional trombone player. Notice the smoothness and predictability in the ascent of the intra-oral air pressure graph (the bottom of the three graphs). Each note is momentarily prepared and after the release, there is a boost of intra-oral air pressure to bring the note to the desired SPL .[2]

Now contrast the results of the professional player with the graph on the right displaying a student's performance of the

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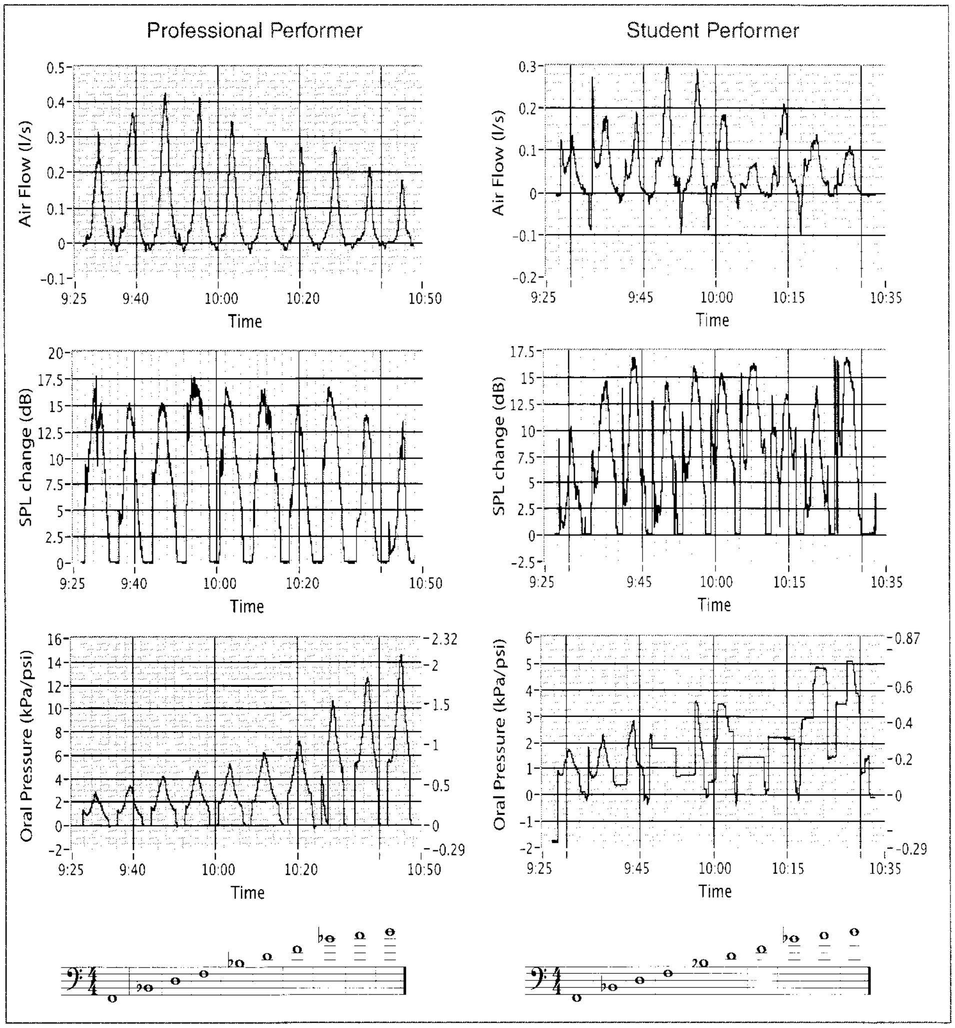

Figure 2: Airflow, SPL & intra-oral pressure on an ascending arpeggio on the trombone by a professional (left panel) and a student (right panel).

same ascending arpeggio. As can be expected the student had far more difficulty controlling intra-oral air pressure, the airflow and, as a result, the SPL as well. Most clearly deficient, however, was the preparation of the onset pressure.

The results of this study also revealed that there is a fairly large range of intra-oral air pressure for any single note. As previously mentioned there is a minimum onset intra-oral air pressure required to reach any given pitch at its minimum SPL. There is also a maximum intra-oral air pressure before the pitch "pops" to the next overtone in the series. This range determines the accessible SPLs. In addition, the range of pressure increases in the higher register. Therefore it becomes necessary to analyze the data gathered at various SPLs. In short, it's possible to play several different consecutive notes (for instance, within any given overtone series) utilizing the exact same intra-oral air pressure, but different SPLs. Figure 3 shows how changes in intra-oral air pressure are connected to airflow for various pitches and SPLs. In Figure 3 the notes in the ascending arpeggio performed by the professional trombonist in Figure 2 are displayed vertically. The graph shows linear fits to the directly obtained data, illustrating the trends without the obscuring factor of momentary variations. Each pitch branches out from the left axis on the graph. The height at which each pitch begins is the minimum onset intra-oral air pressure necessary to begin the note. As each pitch continues, the graph lines move upward to the right indicating an increase in SPL. The lower pitches progress farther to the right of the graph, indicating a greater increase of airflow in the horn compared to higher pitches. Higher pitches require greater increase in pressure, but smaller increases of airflow. Following a horizontal line across the length of the graph illustrates that each intra-oral pressure intersects several different pitches at different SPL levels.

For some, this would seem to lend credence to the argument of those advocates of techniques thought to control pitch by manipulating the intra-oral air pressure: embouchure, position of the tongue, etc. But this is more individual perception than a controlling factor. While individuals may perceive that their strategies are mostly influencing their ability to control pitch, what we know is that changes in intra-oral air pressure are not uniquely associated with pitch unless loudness is held constant.

That being said, the assertion of Jacobs, Bouhuys, Fletcher, and Tarnopolsky that intra-oral air pressure increased with pitch was true. But that does not necessarily mean that the pressure increase *causes* the higher pitch. It is equally likely that the pitch rises for some other reason (*e.g.*, more lip tension) that then requires a concomitant rise in oral pressure. On the other side of the debate, pedagogical methods that advocate controlling higher and lower intra-oral air pressure to affect changes in register are usually an incomplete explanation of the role of intra-oral air pressure.[3]

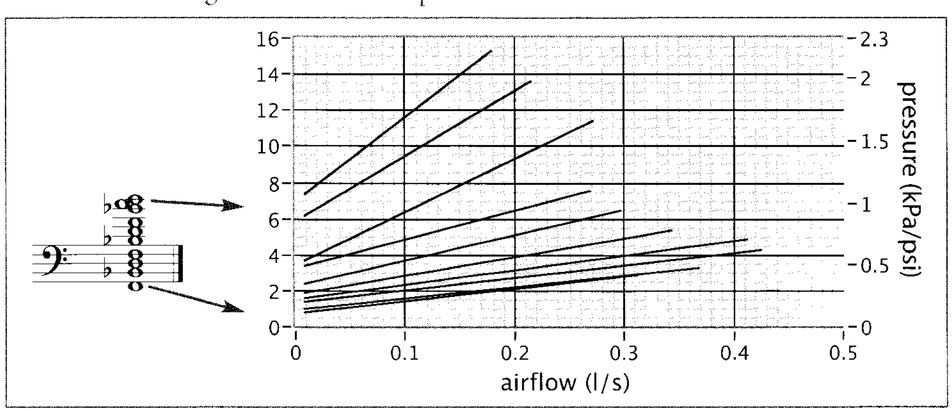

Figure 3: The relation between intra-oral pressure and airflow (in liters/second) for various pitches (different lines) and SPLs (position along a line, louder to the right).

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So, let's return to the original study of Arnold Jacobs. Figure 4 displays the onset intra-oral air pressure readings for the wide range of pitches (frequencies) generated by tuba, trombone, horn, and trumpet. In Figure 3, the onset pressure is the oral pressure at zero airflow, which the player must set up before releasing the note.

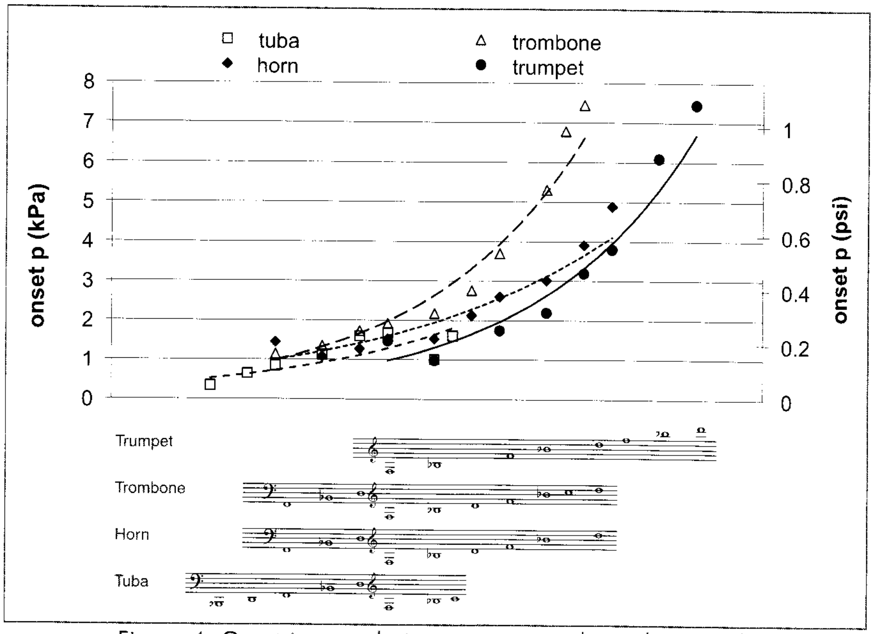

Figure 4: Onset intra-oral air pressure as it depends on pitch across the family of brass instruments.

It is immediately apparent that the intra-oral air pressures for the four different instruments vary widely at a specific pitch. For example, the highest pitches on the trombone and trumpet generate the same intra-oral air pressure, yet their respective pitches are an octave apart from each other! This is in direct contradiction to Arnold Jacobs's claim that intra-oral air pressure is consistent with enharmonic pitch regardless of which brass instrument is playing. This begs the question: where did Jacobs go wrong? One can only conjecture that his misinterpretation of the readings may have been caused by only examining the results across the four instruments in the their collective low to mid-registers. Indeed there are some pitches, the first note that the trumpet plays, for example, where the intra-oral air pressure for all four instruments appears to be rather similar.[4]

"...the effort that is generated by the body is in direct relationship to the standing wave (overtone series) of the horn, regardless of the instrument."

However, this graph does reveal some fascinating consistencies that help to truly understand the role of air when playing a brass instrument. If the results of Arnold Jacobs's first study were somewhat problematic, his initial instinct to create these measurements was inspired. This graph serves as a sort of Rosetta stone. For instance, consider the trumpet and trombone curves: they are nearly identical except for an octave difference in pitch. Accounting for the instrument sizes, the same onset pressures are used to sound the same partials of the instrument.[5]

So what does that mean in brass player laymen terms? It means that the effort that is generated by the body is in direct relationship to the standing wave (overtone series) of the horn, regardless of the instrument.[6] A trombone player has to generate approximately the same amount of intra-oral pressure to play the 8th partial of an overtone series, as does the trumpet. This does not mean, however, that the trumpet and trombone on a given partial are the same in all respects, of course. Before we examine the differences, we'll first need to consider the topics of sound pressure level and airflow and how they relate to intra-oral air pressure.

Sound pressure level (SPL) is perhaps the most overlooked of the three air measurements. Because the physiological signal from our brain to our body that generates more or less SPL is also involved, albeit to a lesser degree, with generating higher and louder pitches, brass players often employ this signal indiscriminately.[7] In other words, it is often the case that players play more loudly as they ascend and more softly as they descend. In the course of the data collection in this study, 100% of the participants increased their decibel level when asked to perform the first ascending arpeggio. It was only afterwards, when asked to maintain a consistent SPL level while ascending that the participants used different mechanisms to ascend in register. When asked to do this, several of the participants actually perceived that they were playing softer as they were ascending even though they were in fact maintaining the same SPL level.[8]

The third effect measured was airflow through the instrument. This data is defined by a flow rate measured in liters per second (lps).[9] In the world of brass pedagogy the discussion of airflow rate can frequently be a source of miscommunication. What a brass player perceives as greater air flow is not always directly correlated to an actual greater volume of air passing through the instrument. The act of flowing air through the horn often has a positive forward moving connotation to the perception apparatus of a brass player. So, because perceived airflow is not the same as actual airflow, it is often the case that a brass players or teachers who relate that they are consciously moving more air through the horn may in fact be moving a great deal less than the student they are addressing. So how much air actually does move through the instrument? This is best displayed in the following graph. Herein lies one of the most crucial discussions between the different camps of players' discussion regarding role of intra-oral air pressure and airflow in the different brass instruments and perhaps some insight as well in the beliefs of Arnold Jacobs.

Figure 5 is a representation of airflow from the same exercise as displayed in Figure 4. On each note, the brass player played a crescendo to fortissimo. Figure 4 records the highest airflow reached at that maximum dynamic. Relative to Figure 5, however, the order from top to bottom has now changed with the horn taking the lowest airflow position and the tuba being directly above it. Why does the horn have the lowest airflow and not the tuba? Indeed Jacobs asserts many times that the flow rate should be greatest in the lower register (and therefore the tuba as well) and the least when playing in the higher reg-

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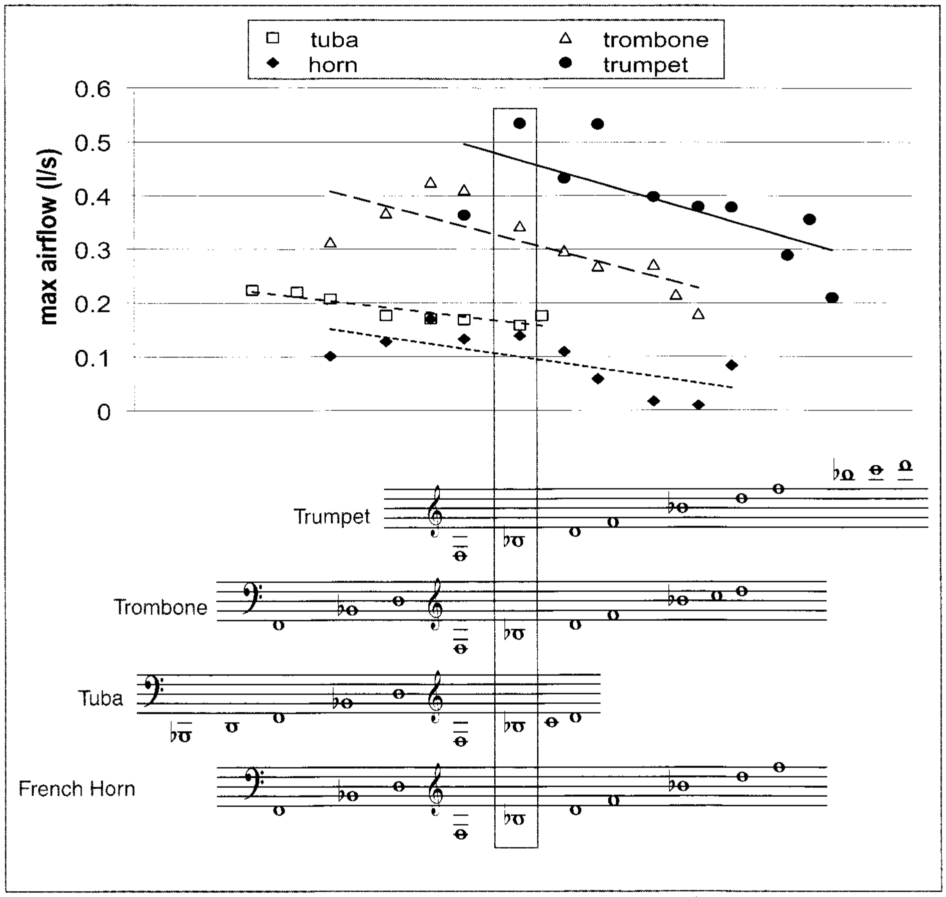

Figure 5: Airflow as it depends on pitch across the family of brass instruments at the same dynamic marking (at the end of a crescendo).

ister (he specifically cites the trumpet as a low flow rate instrument). He then goes further to conjecture that there would be a continuum of change in flow rate that would fall gradually through the family of brass instruments (Fredericksen, 1996, p. 120). However, like his theory that intra-oral air pressure is consistent with enharmonic pitches across the family of brass instruments, he and his colleague Burrows didn't interpret the data correctly.[10] On the graph, one can observe that at any given enharmonic pitch the airflow is markedly different on each of the brass instruments. Observe for example the set of icons that represent the airflow on the pitch b-flat (low C on the B-flat trumpet).[11] Without question the trumpet has the highest flow rate of the four instruments, followed by the trombone, then the tuba, and horn. If you compare this same pitch with the graph displaying intra-oral air pressure (Figure 5), the order is the opposite. The trumpet has the least amount of intra-oral psi and the horn has the most. Again, this is seemingly in direct opposition to Jacobs's statements about the tuba being a high airflow rate instrument with small intra-oral air pressure (in its typical range) and the trumpet being a small airflow rate instrument with large intra-oral air pressure. What is the cause of this result?

"Without question the trumpet has the highest flow rate of the four instruments…"

Consider again that intra-oral air pressure is primarily related to the partial number above the fundamental of an individual brass instrument. On a particular instrument, to reach a higher pitch one creates that pressure by increasing the resistance at the embouchure. It stands to reason then that the more tension that is generated in the lips, the more resistance to the airflow and therefore less airflow in the horn. The low C on a B-flat trumpet is one of the "easiest" notes to play on the instrument. This ease essentially arises from the small amount of physical effort that the body has to generate to produce it. Combined with a need for a greater SPL on lower pitches, this would account for Jacobs's observation that lower pitches require greater airflow.

But changing to a different instrument can change the picture entirely. In the sequence tuba – trombone – trumpet, the mouthpiece becomes smaller. But to produce the same pitch, the intra-oral pressure must either decrease or remain roughly the same. As a result, the embouchure tension must decrease, resulting in a larger airflow. The low airflow in the case of the horn may partially be due to airflow resistance in the long and narrow tubing itself, along with the relatively high intra-oral pressure required. In other words, because the low C on the B-flat trumpet is a much closer to its fundamental than the same enharmonic pitch is on the trombone, tuba or horn, it requires much less physical effort to create it, thus as a result, the lips are more relaxed. This relaxation results in more airflow through the lips.

That being said, the musical demands of the different instruments can easily lead to a misperception of the airflow required for successful performance. The tuba was designed to play in its low register and more often than not, the music written for it will involve playing in a register with lower partials above the fundamental. Combined with a need for a greater SPL, this would account for Jacobs's perception that the tuba is largely a high flow rate instrument. Conversely, the trumpet's musical demands frequently place it in a register of higher partials, thus decreasing its airflow through the instrument.

The relationship of intra-oral air pressure to airflow (Figure 3) for various SPLs enables us to generate a formula where the intra-oral pressure p can be expressed as:

$$p = p_0 + RQ$$

where p_0 is the onset pressure, Q is the airflow, and R is the differential airflow resistance. Both p_0 and R increase with pitch and vary between different instruments. For comparison to other studies, note that R is the flow resistance, not the acoustic impedance, because it relates continuous flow to constant pressure, not vibratory values. Also note that R is a characteristic of the combined instrument and embouchure, not the instrument alone. As such, its increase with pitch is as much a result of performance technique as it is of physical relationships. The "differential" part of term simply indicates that pressure and flow are not directly proportional.

Using this formula to estimate resistance to internal air pres-

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sure (embouchure tension), a more detailed comparison can be made not only between the effort required for different instruments within the brass family but also between two like instruments playing the same pitch. It could even be taken further to compare the same performer playing the same pitch on two different horns, mouthpieces or, in extreme cases, embouchure settings. This pressure-tension relationship lends credence to observations by performers and scientific investigations that tension in the vibrating mass of the embouchure affects the resultant tone quality, as measured by the peak harmonics in the sound spectrum (Fletcher, N.H., and A. Tarnopolsky, pp. 875 – 876). In short, given the same amount of intra-oral air pressure, the more tension introduced to the center of the embouchure will diminish the peaks of the harmonic spectrum, thus resulting in a duller, darker, and softer sound quality.[12]

Frequently, brass instructors give their students instructions on how to achieve greater success by modifying the stream or column of air. These modifications include such metaphors as thicker air, faster air, slower air, hissing, raise or lower the tongue, etc. These modifications of the air stream obviously have some effect on brass performance or well-meaning educators would not be using them. The few scientific studies that have been made of these kinds of modifications have been largely overlooked—a result of being written in a language too far removed from practitioners. There were several studies in the 1950s and 1960s that used cinefluorographic and videofluorographic techniques to examine the movement of the jaw, mouthpiece, tongue, and pharynx while several trumpet and trombone players performed a series of exercises. On the surface, these studies were largely inconclusive as they showed a wide variety of results. However, with deeper examination there are some consistencies that come to light. Movement of jaw, mouthpiece, tongue, and pharynx are indeed most often connected with an ascent in register. However, this movement is, for the most part, minimal and takes place most dramatically as performers approach the limit of their individual upper register. Also, the movement of the tongue from a lower to a higher position, more often than not, did not resemble the same movement that takes place with simply vocalizing the vowel syllables without the addition of the instrument. Unfortunately all of these studies lacked simultaneous measurements of intra-oral air pressure and subsequent airflow through the horn (Frohrip, 1972. pp. 112 – 113). The simultaneous examination of any of the air modifiers coupled with measurements of intra-oral air pressure and subsequent airflow could provide a more definitive answer as to the cause and effect relationship between the two. In summary, the general conclusion that can be gleaned from these previous studies is that, unless taken to extreme, all of the aforementioned air modifying systems (as well as many others) have very little to no effect on intra-oral air pressure and subsequent airflow.[13] This would suggest then that their purpose is for the most part concerned not with changing register or SPL levels to any significant degree, but rather they are either employed consciously to manipulate other adjacent physiological systems; *i.e.,* the embouchure, or their movement is a direct result of a nearby physiological system that is being moved and they are inadvertently along for the ride. Obviously, this discussion bears much greater examination—more then can be dealt with within the confines of this article. Because these systems have actually more to do with altering the shape of adjacent physiological systems rather than the air itself, a more detailed examination of their role will be discussed in subsequent articles.

Summary

Air is the fundamental carrier of energy from the body that excites the vibration of a brass instrument. Pedagogical methods that focus on altering the intra-oral air pressure to facilitate differences in register have failed to distinguish between how intra-oral air pressure affects SPL and how it affects pitch. Methods that focus on more airflow through the brass instrument fail to clarify that airflow is a result of the amount of intra-oral pressure vs. mass and tension of the vibrating portion of the lips. Therefore a performer must either decrease the resistance in the lips and/or increase the intra-oral air pressure to increase airflow. Thus, both methodologies, either one centered on increasing intra-oral air pressure (by blowing harder and/or increasing tension in the lips) or one focused on increasing airflow in the instrument, are dealing with resultants, at best secondary by-products of other underlying functions. Advocates of methods promoting increased airflow are more often than not confusing actual airflow (and its steady and forward moving connotation) with effort and concentration.[14] In other words, "Song and Wind" is more about song than wind. Methods designed to alter the amount of intra-oral air pressure (compression) often fail because these signals from the mind to the body frequently affect other muscle groups including more tension in the vibrating mass of the embouchure, tongue, and throat, thus resulting in even less desirable results.

In its relation to brass performance, one's perception of air can vacillate greatly. Its role swings between the extremes of elemental conditions. At the front and rear end (inhalation and exhalation) of the act of playing a brass instrument, it is a gas. However, when inside the body, depending on the amount of pressure that is placed upon it, it may be perceived as a fluid and perhaps even a solid as the performer experiences focused control.

Future Investigation

Very little has been investigated on the effects that adding tension to the center of the vibrating mass of the embouchure has on the other work systems of the body. Most of the studies that have been done previously have measured only single systems such as mouthpiece pressure, posture, etc. To understand whether tension associated with embouchure tension impedes or supports performance, one must simultaneously examine the interconnections between air flow, intra-oral pressure, and measures of tension. The authors of this article have investigated this subject and presented their initial findings at the International Trumpet Guild Conference in Sydney, Australia, in 2010.

Endnotes

1. One source of confusion in previous studies regarding intra-oral air pressure is in the way that the results have been measured. Most traditionally it has been measured in kPa (kilopascal). North American brass players more easily relate to psi (pounds per square inch). In addition, the measurements taken in previous studies often included standing barometric pressure readings, which varies with the weather but plays no part in production of sound. In short the given barometric pressure on the day that our

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studies were taken hovered around 97 – 98 kPa. (The pressure 100 kPa very nearly equals 14.5 psi.) Thus while it might take 15.5 psi to play a high C on the trumpet at 85dB (forte), it really only takes approximately 1 psi above barometric pressure. Taking this measurement clarification into account could lend some credence to previous studies that have focused on extreme high-note players, claiming that some could generate sufficient intra-oral air pressure equal to the air pressure in an auto tire (25 – 30 psi). If you include standard barometric pressure then yes, players who play in the extreme upper register do easily exceed pressures of 20 psi.

2. The use of SPL as a method to compare sound energy production across different instruments was the most accessible if not necessarily the most reliable measurement for the participants in the study. In this paper, all inter-instrument SPL comparisons are only relative. Because SPL was calculated from sound waveforms, the levels presented are relative to an unknown baseline. Although the distance from bell to microphone was consistent with previous studies and consistent throughout this study, no attempt was made to determine absolute sound power output. Participants were directed to deliver the exercises at a variety of specified dB levels as well as sustained crescendos and decrescendos.
3. This statement alludes to the role of intra-oral air pressure and its ability to affect the shape of the vibrating mass. Because of the complexity of this issue, discussion about it will have to wait until further articles.
4. The results of Jacobs's study may have also been a reflection of the difficulty he encountered with the measuring equipment he was using in discerning minute differences of air pressure immediately above barometric pressure. In addition, within the context of this study, the tuba readings were particularly difficult to measure as we discovered that tuba players (as well as some trombone and horn players) unconsciously open the pharyngeal flap in the rear of their oral cavity (thus releasing air through the nostrils) to decrease intra-oral air pressure as they descend into their respective low registers. This creates an open system that greatly reduces the intra-oral pressure, making it much harder to measure.
5. Although two notes in the exercise were not open/first position, the added length was the same for corresponding pitches. Therefore, the trumpet and trombone curves in Figure 4 are directly comparable. The horn and tuba exercises involved differently fingered notes. These instruments show similar trends, but a careful study of the relation between pressure and partial number needs to be conducted.
6. By way of analogy, imagine that you are holding a whirly tube in your hand and you are about to spin it above your head. The faster you are able to spin it, the higher the realized pitch. Even though it is only the speed of your arm that determines the pitch, your whole body is involved in creating the motion. This would, of course, depend on the length of that tube and its resultant overtone series.
7. This signal from the brain to the body also is connected to a variety of other physical as well as musical phenomenon. In future papers this will be referred to as the mass effort signal. Arnold Jacobs associated this phenomenon with the medical term, Valsalva maneuver. This is a purely physiological response associated with the act of performing a forced exhalation against a closed airway—primarily the lips and closed nose, or in a modified way, against the glottis. The more physiologically specific Valsalva maneuver involves a smaller set of bodily systems than are involved in the mass effort signal. Again, this discussion will have to wait for future writings.
8. This alone is a significant find for future studies and the ramifications of brass pedagogy are immense, far more then can be dealt with in this brief article. This confusion of the signal to control register or SPL is often one of the key differences between a mature musician and an amateur. The issue is even more confused by the fact that the human ear is progressively less sensitive at lower frequencies. Thus, even as the players experienced a constant SPL as a decrescendo, the loudness (in perceptual terms) was actually increasing.
9. Like the measurements for intra-oral air pressure, previous studies of airflow have used a variety of units. Arnold Jacobs described airflow in terms of liters per minute. Arend Bouhuys's article on pressure–flow events in wind playing generated similar readings in (lps) for trombone players as the results found in this study.
10. One might be tempted to wonder about the air *velocity* (in meters per second) instead of the air flow (in liters per second). However, the increase of bore size for lower instruments means even larger distinctions between the air velocities in different instruments on an enharmonic pitch. The only qualitative difference from Figure 5 is that the air velocity in the horn would fall between the trombone and the tuba.
11. It is of interest here that the particular trumpet data in this graph shows a marked deviation from the trend line on the first two pitches, concert F3 and B-flat3. On the B-flat trumpet this translates to a low G and low C respectively. The low G was tentatively performed, producing a low airflow rate. The low C was much more readily produced and the confidence of response resulted in a much higher flow rate than the trend line (and higher SPL as well).
12. Arban, J.B., Goldman, E.F., Smith, W.M., *Arban's Complete Conservatory Method For Trumpet.* Carl Fischer, Inc. (1982). P. 283. "On the cornet, as with the voice, clear tones may be obtained by widening the lips and veiled tones by contracting them."
13. There is an important distinction to be mentioned here, especially when it comes to the role of the position of the tongue and the effect of intra-oral air pressure in the oral cavity. The raising of the tongue can more directly affect the intra-oral air pressure in the oral cavity if the air column only exists from the pharyngeal opening (throat) forward. In other words if air is pressurized only in the oral cavity and the abdomen and chest areas are excluded, then the raising of the tongue can dramatically effect the amount of intra-oral air pressure directly behind the vibrating lips. If the column of air extends all the way from the diaphragm to the lips, then the act of raising and lowering the tongue has much less to no effect at all on intra-oral air pressure in the oral cavity.
14. The body of etudes referred to as "flow studies" is an excellent example of this kind of misnomer. These etudes are usually composed of a continuous stream of slurred sixteenths (or fast eighths) that traverse the length of a page

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or more. There are many examples of these kinds of etudes in the literature including such examples as the Clarke Technical Studies for the Cornet, Charlier Etude #14, and Brandt Etude #31. Students encountering these kinds of studies are frequently advised to approach them with a steady flow of air and idealistically achieve an even color or timbre of sound throughout the etude. The results of this scientific study prove, however, that there is a distinct difference between what is perceived by the ear as an "even flow of pitches" and the wide amount of variation in intra-oral air pressure and airflow that are necessary to achieve them.

References

Barbenel, J.C., Kanny, P., White, J.B., "Mouthpiece forces produced while playing the trumpet," *Journal of Biomechanics*, Vol. 21, No. 5 (1988), pp. 417 – 424.

Basmajian, J.V., and E.R. White, "Electromyographic analysis of embouchure muscle function in trumpet playing," *Journal of Research in Music Education*, Vol. 22, No. 1 (1974), pp. 292 – 304.

Basmajian, J.V., and E.R. White, "Neuromuscular control of trumpeter's lips," *Nature*, Vol. 241, (1973), p. 70.

Basmajian, J.V., and E.R. White, "Electromyography of lip muscles and their role in trumpet playing," *Journal of Applied Physiology*, Vol. 35, No. 6, (1973), pp. 892 – 897.

Berque, P., Gray, H., "The influence of neck-shoulder pain of trapezius muscle activity among professional violin and viola players: an electromyographic study," *Medical Problems of Performing Artists*, Vol. 17, No. 2 (2002), p. 68.

Bouhuys, A., "Lung volumes and breathing patterns in wind-instrument players," *Journal of Applied Psychology*, Vol. 19, No. 5 (1964), pp. 967 – 975.

Bouhuys, A., "Pressure-flow events during wind instrument playing," *Journal of the International Trumpet Guild*, Vol. 7, No. 3 (1983), pp. 11 – 18.

Bouhuys, A., "Sound power production in wind instruments," *Journal of the Acoustical Society of America*, Vol. 37, No. 3 (1965), pp. 453 – 456.

Brandt, Vassily. *Etudes for Trumpet*. MCA Music (1945).

Charlier, Theo. *Thirty-six Transcendent Etudes*. Alphonse Leduc, Paris (1926 & 1946).

Chesky, K., Devroop, K., Ford, J., "Medical problems of brass instrumentalists: Prevalence rates for trumpet, trombone, French horn and low brass," *Medical Problems of Performing Artists*, Vol. 17, (2002), pp. 93 – 98.

Clarke, Herbert L.. *Technical Studies For The Cornet*. Carl Fischer (1912).

Fjellman-Wiklund, Brulin, C., Sundelin, G., "Physical and psychosocial work-related risk factors associated with the neck-shoulder discomfort in male and female music teachers," *Medical Problems of Performing Artists*, Vol. 18, No. 1 (2003), p. 33.

Fletcher, N.H., and A. Tarnopolsky, "Blowing pressure, power, and spectrum in trumpet playing," *Journal of the Acoustical Society of America*, Vol. 105, Pt. 1 (1999), pp. 874 – 881.

Fredericksen, B., "*Arnold Jacobs: Song and Wind.*" Windsong Press (1996).

Frohrip, K. R., "A Videofluorographic Analysis of Certain Physiological Factors Involved in Performance of Selected Exercises for Trombone." PhD dissertation, University of Minnesota, 1972.

Hall, J., "A Radiographic, Spectrographic, and Photographical Study of the Non-Labial Physical Changes Which Occur in the Transition from Middle to Low and Middle to High Registers During Trumpet Performance." PhD dissertation, Indiana University, 1954.

Henderson, H.W., "An Experimental Study of Trumpet Embouchure," *Journal of the Acoustical Society of America*, Vol. 13, (1942), pp. 58 – 64.

Heuser, F., and J. L. McNitt-Gray, "EMG potentials prior to tone production in trumpet players," *Medical Problems of Performing Artists*, Vol. 6, No. 2 (1991), p. 51.

Higel, L.M., "The Relationship of Syllables to Pitch and Tonguing in Brass Instrument Playing." EdD dissertation, University of California, 1967.

Kjelland, J. M., "Application of electromyography and electromyographic biofeedback in music performance research," *Medical Problems of Performing Artists*, Vol. 15, No. 3 (2000), pp. 115 – 118.

Lapatki, B.G., Stegeman, D.F., Jonas, I.E., "A surface EMG electrode for the simultaneous observation of multiple facial muscles," *Journal of Neuroscience Methods*, Vol. 123, Issue 2, (2003), pp. 117 – 128.

Lewis, E. L., "A Photographic Study of the Body Positions of Sixteen Trumpet Virtuosi While Playing Selected Exercises." PhD dissertation, University of Iowa, 1967.

Meidt, J. A., "A Cinefluorographic Investigation of Oral Adjustments for Various Aspects of Brass Instrument Performance." PhD dissertation, New York University, 1985.

Turnbull, D. R., "An Analysis, Clarification, and Revaluation of Donald Reinhardt's Pivot System for Brass Instruments." DMA dissertation, Arizona State University, 2001.

Wilken, D. M. "The Correlation Between Doug Elliot's Embouchure Types and Playing and Selected Physical Characteristics Among Trombonists." DA dissertation, Ball State University, 2000.

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