

Flute Playing Physiology

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A Collection of Papers on the
Physiological Effects of the Native American Flute



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This collection of five papers reflects various aspects of research done on the physiological effects of the Native American flute. Versions of each of these papers have been published elsewhere. This table of Contents provides the citations of the five papers, as published, and a brief description of their intent and contents.

Table of Contents

[Goss 2014] Clint Goss and Eric B. Miller. “Your Brain on Flute”, *Overtones*, May 2014, published by the World Flute Society, pages 10–14.

An article is intended to be accessible to a general audience. This article was edited by Kathleen Joyce-Grendahl.

[Miller 2014] Eric B. Miller and Clinton F. Goss. “An Exploration of Physiological Responses to the Native American Flute”, ISQRMM 2013, Athens, Georgia, January 24, 2014, <http://arxiv.org/abs/1401.6004>. Also available in the *Second Biennial Conference of the Interdisciplinary Society for Quantitative Research in Music and Medicine*, Steve Jackowicz (editor), pages 95–143, ISBN 978-1-62266-036-7.

This contains the full version of the results of our study, intended for the scientific community.

[Miller 2014a] Eric B. Miller and Clinton F. Goss. “Trends in Physiological Metrics during Native American Flute Playing”, *Nordic Journal of Music Therapy*. April 29, 2014, <http://dx.doi.org/10.1080/08098131.2014.908944>

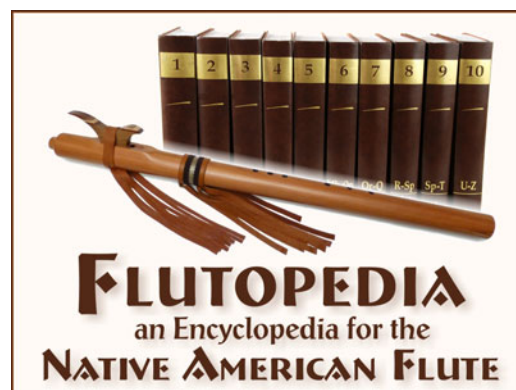
This is a pre-publication version of the article that appears in the Nordic Journal of Music Therapy. This article provides additional information on trends during flute playing that were not previously reported.

[Goss 2013] Clinton F. Goss. “Intraoral Pressure in Ethnic Wind Instruments”, August 21, 2013, 16 pages, <http://arxiv.org/abs/1308.5214>

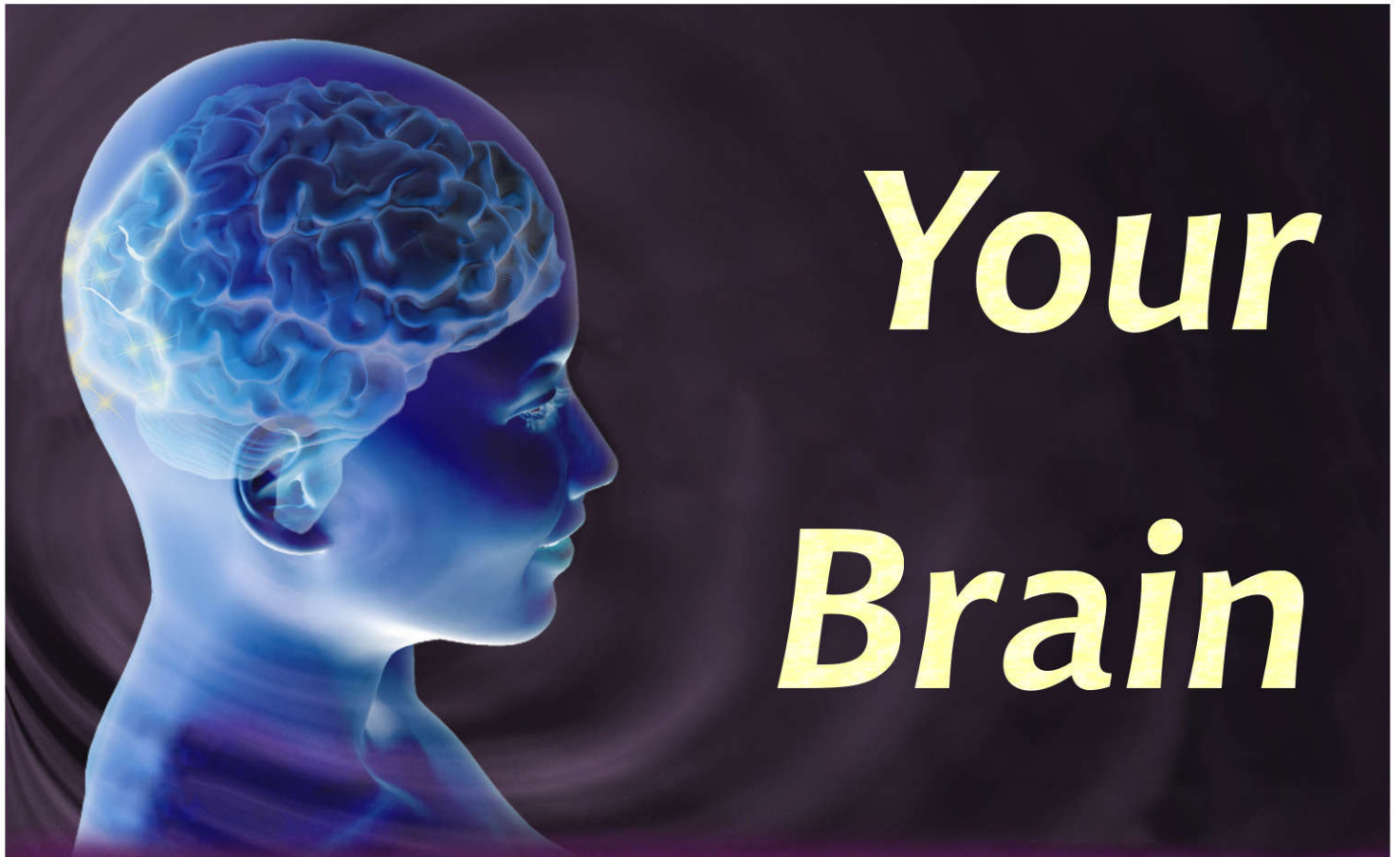
A study of the pressures involved in playing various wind instruments. It compares measured pressures on Native American flutes and other ethnic wind instruments with pressures on other classes of woodwind and brass instruments as reported elsewhere.

[Goss 2013a] Clinton F. Goss and Eric B. Miller. “Dynamic Metrics of Heart Rate Variability”, August 29, 2013, 4 pages, <http://arxiv.org/abs/1308.6018>

A paper detailing the methodology used in measuring Heart Rate Variability in the other studies in this collection.



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Your Brain

on Flute



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A version of this article, edited by Kathleen Joyce-Grendahl, appeared in the May 2014 issue of *Overtone*s, published by the World Flute Society.

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How do we respond, physically and mentally, when we breathe into our flutes? Could the positive effects that we feel from playing flutes indicate a potential use of Native American flutes in music therapy settings? As an alternative therapy for specific clinical conditions, could playing the Native American flute have a place alongside traditional breath-centered practices such as Yoga, Qigong, and Zazen?

Many research studies have explored the effects of *listening* to music (see [Cervellin 2011] for an overview.) Far fewer studies have investigated the effects of *playing* music on our minds and bodies. After an exhaustive search of the literature, we could find only a few studies on the effects of playing Native American flutes, and those studies used self-report methods rather than objective measurements of basic brain and body metrics. So, during the Flute Haven Native Flute School, we carried out a research study to measure the effects of both listening and playing on the heart, nervous system, and brain.

It is common in a single research study to test a very limited set of hypotheses. This approach makes data analysis straightforward and increases the statistical significance of the results. However, our goal was to identify which directions might be fruitful for future

research.

Our curiosity and quest for future directions caused us to look at a wide range of measures and test many hypotheses. This approach, combined with the relatively small number of participants (15 flute players) and several



other limitations, places our research within the context of an “exploratory pilot study”. While we identified several interesting trends and future research directions, we consider the results of this study as “preliminary” and suggest additional research to confirm the effects that we found.

In Brief

We measured brain wave and heart responses while playing flute and listening to flute music.

A key heart metric improved significantly when participants were playing Native American flutes.

Results of this study can give us some guidance when developing music facilitation activities.

There is a potential for using Native American flutes in therapeutic settings for specific clinical conditions.

The detailed results have been recently reported in several articles for the scientific community ([Miller 2014] and [Miller 2014a]). See those articles for a full description of how the study was done and the limitations associated with our results.

This article looks at the results of our research study from the perspective of flute players and facilitators of community music gatherings. What are the preliminary lessons learned? How can we use them as players and facilitators? In this article, we have kept the literature citations to a minimum, since they have been included in our two publications cited above. This article also includes some results that have not been reported earlier.

The Study Outline

We enlisted 15 volunteers to participate in the study from the Flute Haven Native Flute School. Each of them took about an hour off from the program of workshops and playing sessions, bringing two of their flutes a short distance to a lab that we set up for the study. Their flutes were:

- a “lower-pitched flute” – a mid-range E minor flute or lower, and
- a “higher-pitched flute” – a mid-range G minor flute or higher.

Participants were fitted with sensors on their scalp and the fingertip of one pinky to measure heart, skin, and brain activity. Participants then put on headphones and listened to an audio program, which guided them through a program of relaxation periods, listening to several kinds of music, and playing their flutes. Measurements taken during an initial period of silent relaxation served as a “baseline” to compare against measurements taken during later periods of listening and playing.

Throughout the study, we recorded the electrical activity of the brain in seven frequency bands, which provided an indicator of the overall emotional state of the participant. We also recorded the level of skin conductivity, which is an indicator of nervous system arousal and sometimes anxiety. This measure of arousal increases as small moisturized particles (sweat) on the skin are produced.

For heart metrics, we recorded precise pulse-beat measurements at the fingertips. These pulse-beat measurements allowed us to determine three cardiac measures: heart rate, volume of blood flow per heartbeat at the fingertip, and a key metric called “heart rate variability”, which is described below.

Summary of the Significant Results

The chart “Changes in Physiology when Playing Native American Flutes” on the next page summarizes significant results that we found during this study. The remainder of this section provides details and discusses those results. If you find the results in this section too detailed, feel free to skip forward to the “Practical Applications” section near the end of this article.

The effects described below are based on several types of comparisons:

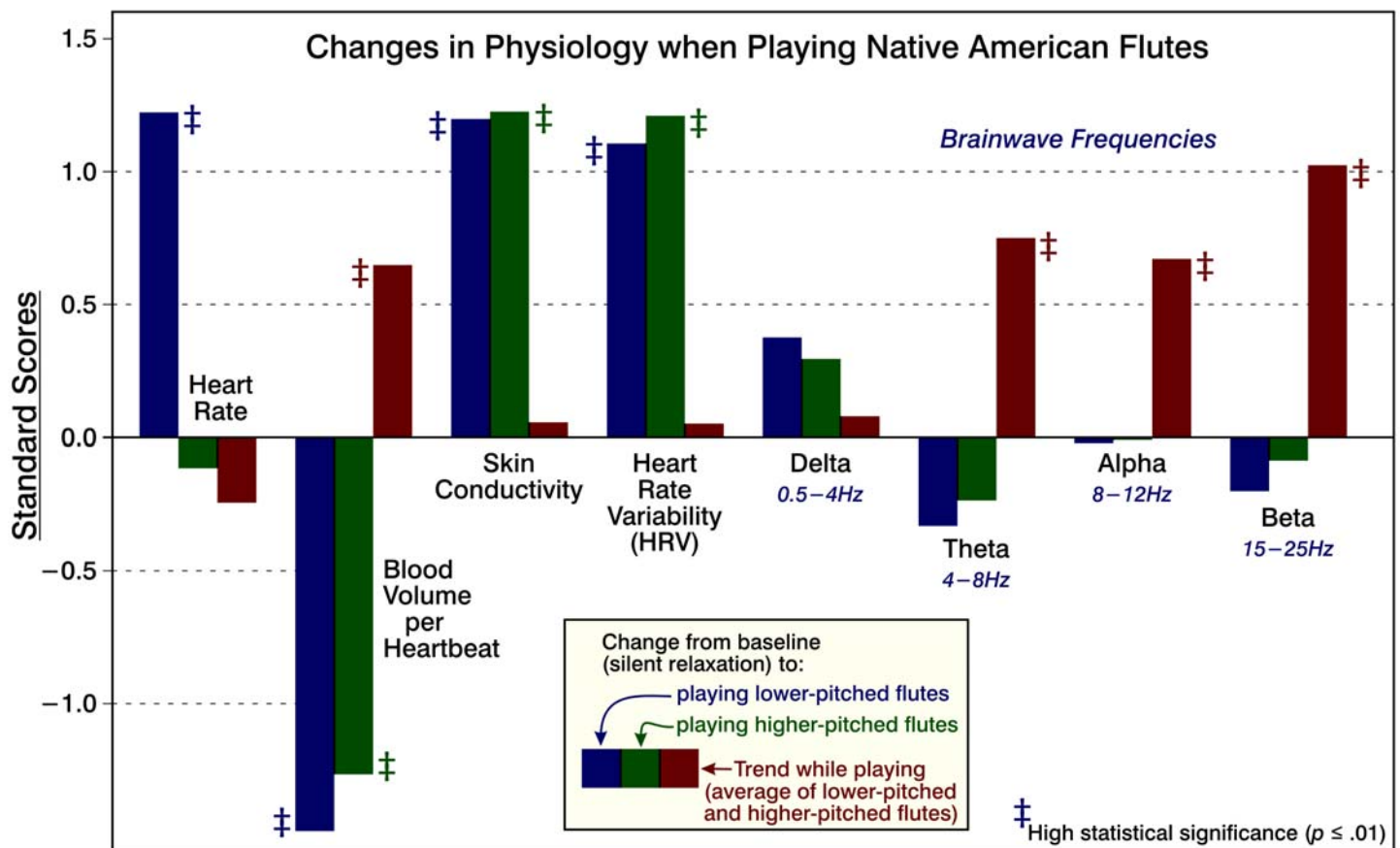
- a comparison between the period of flute playing and a “baseline” period of silent relaxation;
- a “trend” indicating a comparison between the first half and the second half of the period of flute playing; or
- a comparison between the periods of playing lower-pitched flute and playing higher-pitched flute.

Items marked with † indicate that the result showed statistical significance and ‡ indicates a result with strong statistical significance.¹ However, we again stress that, since we tested many hypotheses in this study, the effects that we found need to be confirmed in subsequent research studies with larger populations of flute players.

Heart Rate, Blood Flow, and Skin Conductivity

The first time participants played their flutes during the study, we asked them to play their lower-pitched flute. As we might expect, compared with baseline silent relaxation, their heart rate increased†, they had more skin conductivity‡, and the frequency bands of electrical brain

¹ The † marking indicates a significant result with a paired, two-tailed Student’s t-test result of $p < 0.05$. The ‡ marking indicates a highly significant result with a paired, two-tailed Student’s t-test of $p \leq 0.01$.



activity associated with muscle control increased[‡]. The trend while playing lower-pitched flutes was toward an increase in the volume of blood flow per heartbeat in the fingertips[‡].

During the second flute-playing period, we asked participants to play their higher-pitched flute. Again, skin conductivity increased during flute playing[‡] when compared with baseline silent relaxation, and the trend while playing was toward an increase in the volume of blood flow per heartbeat[‡].

The heart rate of participants was lower during the second flute-playing period than during the first flute-playing period[‡]. This might be expected, again because higher-pitched flutes are smaller and also because there may have been less anxiety during the second flute-playing period. However, contrary to what we might expect, average heart rate when playing higher-pitched flutes was actually *lower* than during the baseline period, when they were sitting in silent relaxation. This divergent response – heart rate decreasing while skin conductivity increased – begs further investigation.

Heart Rate Variability

When you inhale, your heart rate increases. As you exhale, your heart rate decreases. Similar variations in your heart rate occur on longer cycles of minutes, hours, and throughout the 24-hour sleep-wake cycle.

These normal variations in your heart rate are called “heart rate variability” or “HRV.” Higher HRV – i.e. a larger variation in heart rate – turns out to be a reliable indicator of health and general resilience to stress. A very steady heart rate – i.e. low HRV – is associated with a range of clinical conditions such as anxiety, hypertension, COPD, panic disorder, depression, and is also a predictor of sudden cardiac death.

With the goal of effectively treating those clinical conditions, various techniques have been explored to raise HRV. In particular, biofeedback training has been found to have various degrees of effectiveness in the treatment of asthma, PTSD, hypertension, anxiety, COPD, recurrent abdominal pain, music performance anxiety, and fibromyalgia. In the treatment of major depressive disorder, biofeedback training to raise HRV demonstrated

effects that appeared to be stronger than drugs often prescribed for the condition.

Our study found that HRV increased an average of 84 percent when playing Native American flutes when compared with baseline silent relaxation. The increase in HRV compared to baseline silent relaxation was statistically highly significant when playing both lower-pitched flutes[‡] and higher-pitched flutes[‡].

We found that subjects with *less* meditation experience correlated a *greater* increase in HRV. The increase in HRV did not correlate strongly with age, gender, or experience playing Native American flutes, although this could be due to the limited number of participants in our study.

Studies have established that adults typically breathe in cycles of about 3 to 5 seconds. During our study, we found that playing the Native American flute tends to increase the breath cycle to about 10 seconds. Other research has shown that HRV is highest at breath cycles of about 12 to 15 seconds – or about 4 to 5 breaths per minute. We believe that the increased length of the breath cycle that naturally occurs during flute playing is a major factor causing the increase in heart rate variability.

Brain Activity

Several frequency bands of brain activity showed interesting results during the periods of playing.

Alpha. Brainwaves in the range 8 to 12 Hz² – often called the Alpha band – are associated with a light meditative state, relaxation, and closing of the eyes. Alpha waves decrease with eye opening and mental exertion.

During our study, Alpha waves decreased in relation to the preceding silent relaxation period while playing both higher-pitched flutes[‡] and lower-pitched flutes. The trend reversed during the playing period itself, with Alpha waves trending upward during playing for both higher-pitched flutes[‡] and lower-pitched flutes. This suggests a pattern of decreasing Alpha waves during initial playing followed by increasing Alpha as playing continues. This pattern is consistent with participants closing their eyes, relaxing, and attaining a light meditative state, but only after

playing for a period of time – about 90 seconds in this case.

It is also interesting to note that the highest Alpha waves measured during our study were during the two silent relaxation periods that followed periods of listening to music. While it was not a goal of this study to explicitly examine the effects of silence, the enhancement of Alpha waves agrees with prior research that has demonstrated activation of the auditory cortex during periods of musical silence ([Kraemer 2005]), and the positive impact of silence in music on retention and recall ([Olsen 1995]).

The increase in Alpha band activity from baseline silent relaxation to flute playing correlated strongly with years of experience reported by the participants playing Native American flutes. We can surmise that, over time, players become more adept at quickly entering a light meditative state when they begin playing.

Beta. Brainwaves in the 15 to 25 Hz range – termed the Beta band – are usually associated with alert, active thinking or anxious concentration.

Our study showed different reactions in the Beta band for novice and experienced players. When compared with baseline silent relaxation, novice players showed significant *decreases* in Beta activity when playing both higher-pitched[‡] and lower-pitched[‡] flutes while experienced players showed slight *increases* in average Beta brainwave activity during the flute playing periods. We propose two conjectures:

- Less experienced players are not as habituated to the tones of the Native American flutes, where the more experienced players exhibit a reduced novelty effect; and
- More experienced players tend to make greater mental use of music theory rules to create melodies.

Theta. The 4 to 8 Hz range is termed the Theta band. Elevated Theta waves have been found in various studies during creative processes, deep meditation, drowsiness, inattention, and is associated with working memory.

We measured increasing trends in Theta band activity during the periods of playing higher-pitched[‡] and lower-pitched flutes. We also found a significant increase in theta band activity in novice players, but not experienced

² Hz = Hertz = cycles per second

players, between the silent relaxation periods at the very ends of the study† – i.e. between the initial baseline silent relaxation period and a similar period of silent relaxation after all the periods of playing and listening to music.

Our results provide some indications of movement during flute playing towards the attributes associated with increased Theta band activity. The overall experience of the study – listening, playing, and interim silent relaxation – did increase Theta activity in novice players. We suspect that these measured trends would be more robust if longer playing periods were used in future studies.

Delta. The 0.5 to 4 Hz range is termed the Delta band. These slow waves dominate brain activity in adults during slow-wave sleep, a phase of deep, non-rapid eye movement sleep.

When compared with the silent relaxation period preceding the two periods of playing flute, our study found that flute playing had the opposite effect on Delta than it did on Alpha band activity: While Alpha waves *decreased*, Delta wave *increased* for both lower-pitched‡ and higher-pitched flutes†. This increase in Delta showed no significant trends during the flute playing periods.

Practical Applications

Although this broad-based study was not designed to provide definitive answers to specific questions, we can infer some potential guidelines from the results. This section combines the results of our study with information from prior research studies to suggest some practical applications for flute players and facilitators of community music gatherings. A number of assumptions are implicitly made in these suggestions, but we believe they are reasonable.

Breathing Rate

Playing the Native American flute appears to slow breathing rate from about 15 breaths per minute to about 6 breaths per minute. Encouraging players to slow their breath rate a bit further – to about 4 to 5 breaths per minute – may have some health benefits.








One approach we use in workshops is to have people play “one-breath solos” – first on their voices and then

moving to their flutes. Depending on what a person plays, we might ask them to play the same solo slower, hold some of the notes longer, or play it two times in a single breath. These activities combine a memory exercise (repeating the same one-breath solo) with an exercise that slows their breath rate.

Another technique is to have players focus on their inhalation. This type of mental focus often causes players to breathe in more deeply and slows their overall breathing rate. Another technique, used by Cornell Kinderknecht, is to focus on “squeezing out some extra air” from the lungs to extend a phrase.

Length of Playing Time

The lengthy time it takes for flute playing to affect Alpha and Theta waves suggests that longer playing periods are preferable. Longer playing periods are common in community drum circles, but can be a challenge to facilitate in flute gatherings. Here are some ideas of things you can do with the group as a whole, or with segments of the group, while inviting individual flute players to solo:

- Have everyone chirp very short notes to a rhythm that you establish. If the notes are very short, the differences in pitch will not produce too much dissonance.
- Have everyone hold the same long tone as a drone. If people have different key flutes, you can ask them to hold these fingerings, which should all sound roughly the same pitch:
 - D flutes hold  or .
 - E flutes hold .
 - F# flutes hold .
 - G flutes hold .
 - A flutes hold .
 - B flutes hold .
- Establish a simple repeated pattern and have all flutes of a particular key play that pattern. You can engage others in the circle who are not playing the pattern by asking them to create texture sounds, such as the sound of the wind by breathing across the finger holes on their flute.

Showcasing Players

One technique in drum circle facilitation is to showcase a single player, either as a solo or playing above an established pattern. In practice, having that player be more experienced seems to have better results. Experienced players tend to be adept at more musical techniques, and our study suggested that experienced players can enter a light meditative state more quickly when they play. This suggests that players with more experience can quickly become attuned to the group and the situation, and they may also serve as a model for less experienced players on playing “in the moment”.

Using Silence

The effect of silence noted in the previous “Brain Activity” section underscores the general belief among musicians in the power of silence. Jazz pianist Keith Jarrett famously said that “*Silence is the potential from which music can arise*”.

Along these lines, experiment with the effect of adding slightly longer pauses when you play. Does it engage your audience? Do they “lean forward” just a bit?

If you are facilitating a group with a conducted improvisation, you might include an occasional “stop/cut”. This can be done by clearly conducting the entire group from full play to complete silence, then marking four or eight beats of silence before signaling them all to resume playing. You could emphasize this technique by inviting other people in the group to try their hand at conducting a stop/cut.

A common game in small ensembles is to “pass the solo.” With the group engaged in a steady-state repeated pattern, each player takes a turn soloing over the pattern. To incorporate silence, you could ask an ensemble to “pass the *silence*.” After a steady-state pattern is established by the group, players take turns stopping for a few bars. You could make it more challenging by asking them to re-join the music with a different part, and see how the pattern changes as the silence moves around the group.

Disengage the Visual

One of the most powerful techniques we have found for facilitating a deeper listening experience with a group

of flute players is to have them close their eyes. This simple technique helps participants focus on the sound, raises Alpha brainwaves, and seems to reduce any level of anxiety associated with playing in front of other people.

We often use this technique when we want to emphasize an exercise, activity, or teaching point. Simply having the group close their eyes and repeat the activity can be a powerful aid to learning.

Future Directions

Our study is in an area of research that deals with some fundamental questions. What are the physical and mental effects of playing music? What are the implications for music therapy? Is playing music effective as an alternative therapy for specific clinical conditions? Our initial goals were to develop techniques for measuring the effects of Native American flute playing, to record basic metrics of the body and mind, and to identify fruitful directions for future research.

We believe, despite the limitations of our study (described in detail in [Miller 2014]), that these goals have been met. And, in particular, the results showing a significant increase in heart rate variability during flute playing indicates that our exploratory approach to measuring physiological metrics has proved fruitful.

The past several decades have been witness to a profound shift in the practice of Western medicine. In addition to new medicines and procedures for treating the sick, there is a growing focus on wellness care, alternative therapies, and the mind-body connection. Many of these alternative modalities come from traditional practices such as Yoga, Qigong, Tai Chi, various forms of meditation, a broad range of expressive arts, and from biofeedback training.

Many of these alternative modalities share a common focus on the breath. There is a growing body of evidence for the effectiveness of various breath practices on a variety of clinical conditions. Flute playing can also be seen as a breath practice. Is it possible that Native American flute playing could be effective for some clinical conditions? In answering this question, we have a number of indicators:

- Research has established that Biofeedback training to raise HRV is “probably efficacious” for asthma ([Wheat 2010], page 238);
- Our study demonstrated that playing Native American flute raises HRV;
- Throughout the course of this study, we have received many unsolicited accounts from asthma sufferers testifying to the value of playing Native American flutes for their condition;
- There is a body of research showing various benefits of wind instruments on parameters of lung function.

We believe that the confluence of these indicators suggest the possibility of a direct causal link between playing the Native American flute and the reduction of the symptoms of asthma. We suggest that a compelling direction for future research would be a direct investigation of the effect of a music therapy program of Native American flute playing on asthma.

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An Exploration of Physiological Responses to the Native American Flute

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ABSTRACT

This pilot study explored physiological responses to playing and listening to the Native American flute. Autonomic, electroencephalographic (EEG), and heart rate variability (HRV) metrics were recorded while participants ($N = 15$) played flutes and listened to several styles of music. Flute playing was accompanied by an 84% increase in HRV ($p < .001$). EEG theta (4–8 Hz) activity increased while playing flutes ($p = .007$) and alpha (8–12 Hz) increased while playing lower-pitched flutes ($p = .009$). Increase in alpha from baseline to the flute playing conditions strongly correlated with experience playing Native American flutes ($r = +.700$). Wide-band beta (12–25 Hz) decreased from the silence conditions when listening to solo Native American flute music ($p = .013$). The findings of increased HRV, increasing slow-wave rhythms, and decreased beta support the hypothesis that Native American flutes, particularly those with lower pitches, may have a role in music therapy contexts. We conclude that the Native American flute may merit a more prominent role in music therapy and that a study of the effects of flute playing on clinical conditions, such as post-traumatic stress disorder (PTSD), asthma, chronic obstructive pulmonary disease (COPD), hypertension, anxiety, and major depressive disorder, is warranted.

Introduction

The Native American flute, a traditional ethnic wind instrument developed by indigenous Native American cultures, is enjoying a renaissance in various sectors of society. The instrument evolved from traditional uses in courtship (Black Hawk & Patterson, 1834; Burton, 1909), treatment of the sick (Densmore, 1936), ceremony (Gilman, 1908; Stacey, 1906), signaling (Densmore, 1929), legends (Deloria & Brandon, 1961; Densmore, 1923; Erdoes & Goble, 1976; Erdoes & Ortiz, 1984; Wissler, 1905), and as work songs (Densmore, 1957; Winship, 1896).

The design of the Native American flute is “a front-held, open-holed whistle, with an external block and internal wall that separates a mouth chamber from a resonating chamber” (R. Carlos Nakai, personal communication, June 21, 2002, as cited in Goss, 2011). The instrument first appeared in the historical record in the early 19th century, and has been known by various names such as “courting flute”, “love flute”, “plains flute”, “woodlands flute”, and “śi’yotanka” (Densmore, 1918).

The Native American flute is classified in the same family as the recorder.¹ It uses a duct or *flue* to direct the player’s airstream, allowing the instrument to be played without the need for players to learn to form an embouchure with their lips. It is distinguished from the recorder by the inclusion of a slow air chamber which precedes the flue, providing an air reservoir that acts as a modest pressure bladder, tending to smooth out changes in breath pressure. Another distinguishing characteristic is its limited pitch range – typically no more than 1.3 octaves from the lowest note on the instrument.

Figure 1 shows the typical elements used in the design of a Native American flute. Since there are no common design standards, contemporary instrument makers take far more freedom in their designs than makers of orchestral wind instruments.

¹ In the widely-used classification system of Hornbostel & Sachs (1914).

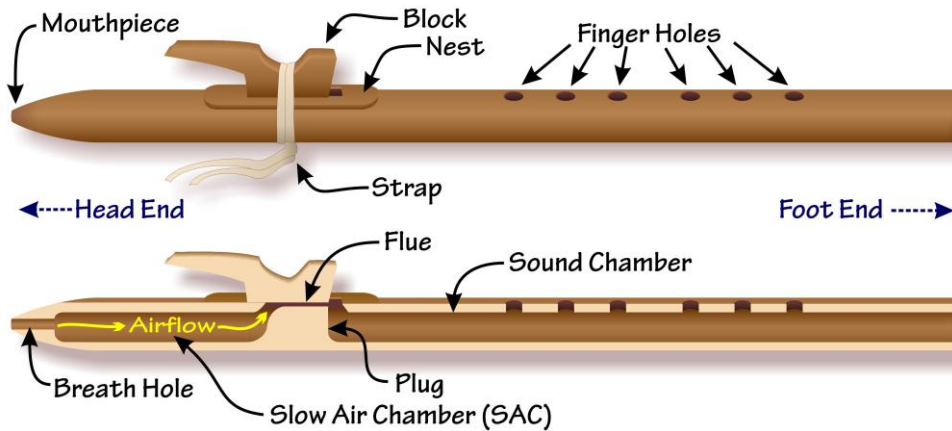


Figure 1. Anatomy of the Native American flute.

Historical Use in Healing

Various forms of flutes and reed aerophones have been used in healing contexts since at least the time of Aristotle (323–373 BCE: [Meymandi, 2009](#)) and possibly as far back as the Third Dynasty of Ur in Ancient Mesopotamia (2100–1900 BCE: [Krispijn, 2008](#)).

A tradition of *flûtes sacrées* (*flautas sagradas* or *sacred flutes*) is found in a number of indigenous South American cultures ([Menezes Bastos & Rodgers, 2007](#); [Piedade, 2004, 2006](#)). The Jesuit priest, [José Gumilla \(1741\)](#), provided an early description of rituals with these instruments and related them to funeral rites held by the Saliva of the Orinoco basin, in present-day Venezuela ([Hill & Chaumeil, 2011](#)).

In North America, indigenous rim-blown flute designs have been depicted in religious music or as part of a magical rite ([Renaud, 1926](#)). Music played on these flutes was used for Hopi religious ceremonies and during medicine preparation ([Hough, 1918](#)).

Wind Instruments in Healing and Therapy

In 1956, after observing that children with asthma who played wind instruments often did exceptionally well in sports activities, [Marks \(1974\)](#) developed a program using brass instruments, which demonstrated improved lung function parameters. This work inspired the development of the long-running *Léčivá Píšťalka* [Active Flute] program ([Komárková, 2012](#)) in the present-day Czech Republic that uses the soprano recorder for children with asthma. The program, presently known as *Veselé Pískání – Zdravé Dýchání* [Merry Whistling – Healthy Breathing] ([Žilka, 1993](#)), has shown significant improvement in respiratory parameters, posture, and breathing coordination after two years of daily wind instrument playing ([Petrů, Carbolová, & Kloc, 1993](#)).

In other studies, [Puhan et al. \(2006\)](#) found that regular playing of the didgeridoo was an effective treatment for patients with moderate obstructive sleep apnea syndrome. The didgeridoo was also found to improve respiratory function and self-reports of health in Aboriginal junior-school and senior-school boys with asthma ([Eley & Gorman, 2008](#)). [Lucia \(1994\)](#) found a reduction in panic-fear responses and mood changes in teenage wind instrument players with asthma versus their

peers who did not play wind instruments.

A number of studies have investigated the relationship between heart rate variability (HRV) and playing musical instruments with respect to performance anxiety and emotion ([Harmat & Theorell, 2010](#); [Harmat et al., 2011](#); [Thurber, 2006](#); [Nakahara, Furuya, Obata, Masuko, & Kinoshita, 2009](#)). However, none have involved the Native American flute.

Native American Flutes in Healing and Music Therapy

The Native American flute has a reputation for a meditative and healing sound that is compatible with New Age music, and is often heard in meditation centers, museum shops, and yoga studios. This instrument is also flourishing in the expanding social phenomenon of *flute circles* – informal social music gatherings that support the use of the instrument by players with little or no formal music training ([Jones, 2010](#)).

In present-day healing and therapy contexts, the Native American flute was reportedly used in hospice care by a music therapist for a Navajo woman ([Metzger, 2006](#)), to meet the emotional and spiritual needs of Aboriginal students ([Dubé, 2007](#)), and in the treatment of anxiety in individuals diagnosed with a trauma-related disorder ([Wiand, 2001, 2006](#)). Aside from these references, a literature search of the ProQuest, JSTOR, and PsychInfo systems yielded no results, demonstrating a paucity of scientific literature seeking to understand the underlying mechanisms behind the cultural tradition that accompanies these instruments.

While [Wiand \(2001, 2006\)](#) was interested in the effect of the Native American flute on anxiety, her measure was by self-report rather than physiological measurement. Her conclusion that Native American flute music appears helpful in treating trauma-related disorder populations is consistent with the popular notion of the Native American flute as a

healing instrument. However, her study also highlights the need for validation via objective physiological measures.

The Present Study

This pilot study explored physiological responses to the Native American flute. This line of inquiry could assist music therapists using the Native American flute in their practices through increased understanding of potential clinical applications of the Native American flute. We monitored electroencephalographic (EEG) brainwaves, heart rate (HR), electrodermographic activity (EDG), and blood volume pulse (BVP). In post-analysis, derivative measures of HRV were also examined.

Four hypotheses were proposed:

1. Listening to Native American flute music will entrain a meditative brain state, discernible in brainwave patterns of increased EEG alpha and theta with reduced beta activity.
2. Listening to Native American flute music will induce a relaxed state, discernible by autonomic measures of reduced HR, EDG, and electromyogenic activity (EMG), with increases in BVP and HRV.
3. Playing Native American flute will entrain a meditative brain state, discernible in brainwave patterns of increased EEG alpha and theta with reduced beta activity.
4. Playing Native American flutes will induce a relaxed state, discernible by autonomic measures of reduced HR with increases in BVP and HRV.

This investigation also explored differences in the effects of playing a lower-pitched Native American flute versus a higher-pitched Native American flute and differences in the effects of listening to several different styles of flute music as compared to sitting in silence.

Method

A convenience sample of 15 Native American flute players was taken from volunteer participants at the 2009 Flute Haven Native Flute School. These flute players did not necessarily have Native American heritage. Participants signed an informed consent and agreed to participate in and of their own free will with an understanding that they could withdraw at any time. Participant data was de-linked from identifying information to protect confidentiality.

Participants varied in gender and in their amount of experience playing Native American flutes.

Participants were asked to bring two of their own Native American flutes to the study: A *lower-pitched flute* with a lowest attainable pitch in the range A_3 – E_4 (220.0–329.6 Hz)²

and a *higher-pitched flute* with a lowest attainable pitch in the range G_4 – E_5 (329.0–659.3 Hz).

Participants were fitted with a non-invasive EEG sensor at Cz, ear clips for reference and ground, and a finger sensor for autonomic measures on a non-playing finger. All participants listened to the same sequence of instructions, silence, and periods of music on closed-cell headphones.

Study Outline

Following pre-recorded instructions, the study conditions comprised:

1. Baseline silence.
2. Listening to solo flute. “Canyon People” (Nakai, 1993, track 7) consists of solo Native American flute in *parlando* style – with no meter or definitive rhythm.
3. Interim silence 1.
4. Playing lower-pitched flute. Participants were asked to play their lower-pitched flute.
5. Listening to rhythmic flute. “Lost” (Ball, 2002, track 6) is a highly rhythmic piano pattern with a melody played on a Native American flute.
6. Interim silence 2.
7. Playing higher-pitched flute. Participants were asked to play their higher-pitched flute.
8. Listening to melodic cello. “Prayer for Compassion” (Darling, 2009, track 2) is a polyphonic, melodic composition containing numerous layers of cello.
9. Post-baseline silence.

Conditions were approximately two minutes in length, except for the two shorter interim silence periods.

Autonomic Metrics

Autonomic metrics were sampled at 24 Hz using a MindDrive™ finger sensor (Discovogue Infotonics, Modena, Italy). The finger sensor contained both an electrodermal and a photoplethysmographic (PPG) biosensor. The PPG biosensor measures light transmission through tissue and provides a relative measure of instantaneous peripheral blood volume. Once these readings are calibrated around a zero axis, crossings from negative to positive readings were identified as upward zero crossings. The timespan of a pulsebeat was the time between two neighboring upward zero crossings. Processed data for HR, BVP, and EDG were recorded at one-second intervals.

Electrodermographic readings. EDG was taken via finger sensor that provided a measure of electrical conductivity of the skin. Eccrine glands produce minute moisturized particles (sweat) which increase skin

² The note names in this paper are based on Young (1939).

conductivity. Eccrine gland output increases with nervous system activation. Galvanic skin response (GSR), measures skin resistance and is an inverse indicator of EDG. Both EDG and GSR measures of electrodermal activity have been used extensively in psychological research and are common measures of autonomic nervous system activity (Andreassi, 2006; Mendes, 2009).

Blood volume pulse. BVP is a relative measure of peripheral blood volume.

Heart rate. The HR metric consisted of PPG-recorded pulsebeats in beats/min.

Heart rate variability. HRV is the fluctuation in time intervals between adjacent cardiac cycles. Maximum HR minus minimum HR was calculated within estimated breath cycles of 10 (EBC10) and 16 seconds³ (EBC16) averaged over discrete consecutive windows of those time periods. Both EBC metrics have been shown to correlate very strongly with SDNN – the standard deviation (SD) of intervals between R peaks in adjacent cardiac cycles from normalized ECG data (Goss & Miller, 2013). ECG-derived measures of HRV are the “gold standard” of HRV measurement (Selvaraj, Jaryal, Santhosh, Deepak, & Anand, 2008). Russoniello, Zhirnov, Pougatchev, & Gribkov (2013) showed very strong correlations between HRV metrics from PPG and ECG data.

EEG Metrics

Readings from a monopolar EEG sensor placed at Cz were acquired through a BrainMaster™ 2E system (BrainMaster Technologies, Bedford, OH), taken at 256 Hz. Particular attention was given to these EEG bandwidths:⁴

- Delta (0.5–4 Hz), dominates EEG spectral activity in adults during slow-wave sleep, a phase of deep, non-rapid eye movement sleep (Silber et al., 2007);
- Theta (4–8 Hz), usually found during creative processes and deep meditation (Gruzelier, 2009; Miller, 2011; Wright, 2006), as well as working memory (Vernon, 2005) and drowsiness and inattention (Gruzelier & Egner, 2005);

- Alpha (8–12 Hz), associated with a light meditative state (Gruzelier, 2009; Miller, 2011; Wright, 2006), appearing with closing of the eyes and with relaxation, and attenuating with eye opening or mental exertion (Jensen et al., 2005; Lucking, Creutzfeldt, & Heinemann, 1970; Yang, Cai, Liu, & Qin, 2008);
- Sensorimotor rhythm (SMR) (12–15 Hz), inversely related to motor activity or motor imagery (Gruzelier & Egner, 2005; Lubar & Shouse, 1976; Monastra et al., 2005) and positively associated with semantic working memory (Vernon, 2005);
- Beta (15–25 Hz), usually associated with alert, active cognition or anxious concentration (Gruzelier & Egner, 2005; Miller, 2011); and
- Gamma (35–45 Hz), thought to represent neuronal activity that links several distant areas of the brain in a single function (van Deursen, Vuurman, Verhey, van Kranen-Mastenbroek, & Riedel, 2008; Wright, 2006).

In some cases, we also analyzed wide-band beta in the frequency range 12–25 Hz as well as theta and alpha in the range 4–12 Hz. We also monitored muscle movement artifact using an algorithm that processed EEG activity in the 25–35 Hz band.⁵ This provided a convenient indication of potential EEG signal contamination.

Analysis

Following acquisition, data artifacts were identified with a software algorithm based on the standard score for each data point. Data points exceeding $\pm 4\sigma$ were then removed during a visual inspection phase.

Participants were categorized for analysis by experience, gender, and age:

- novice (less than 3 years of experience playing Native American flutes, $n = 7$) versus experienced ($n = 8$) flute players;
- male ($n = 10$) versus female ($n = 5$); and
- younger (less than the median age of 58.4 years, $n = 8$) versus older ($n = 7$).

³ The length of estimated breath cycles while playing flute are supported by an informal breathing-rate survey conducted concurrently with this study. Native American flute players ($N = 28$, mean age = 59.9 years) self-assessed the number of inhalations taken during one minute of “normal or average playing” on various flutes. Their reports average 10.31 seconds per breath cycle ($SD = 4.51$). Compared with a normal respiratory cycle of 3–5 seconds in adults (Lindh, Pooler, Tamparo, & Dahl, 2009), flute players tend to extend their breath cycles while playing.

⁴ The characteristics described for the EEG bands are a simplification provided for general background and do not reflect the diversity of associated functional states and neural communications (Gruzelier & Egner, 2005).

⁵ The algorithm for deriving EMG from EEG data was used in the Lexicor NRS–2D series of neurofeedback training machines. While those particular machines shipped with a default software setting that designated amplitudes of 25–32 Hz over 15 μV as EMG artifact, a study of attention deficit/hyperactivity disorder conducted by the City of Philadelphia Office for Mental Health (Berman, 2001) used a slightly more conservative bandwidth: 25–35 Hz averaged over 250 ms to detect more muscle activity (Marvin Berman, personal communication, April 8, 2000). The premise is that, while EMG artifact cuts across the entire spectrum of 0–100 Hz, a representative sample may be acquired from just above the Beta range.

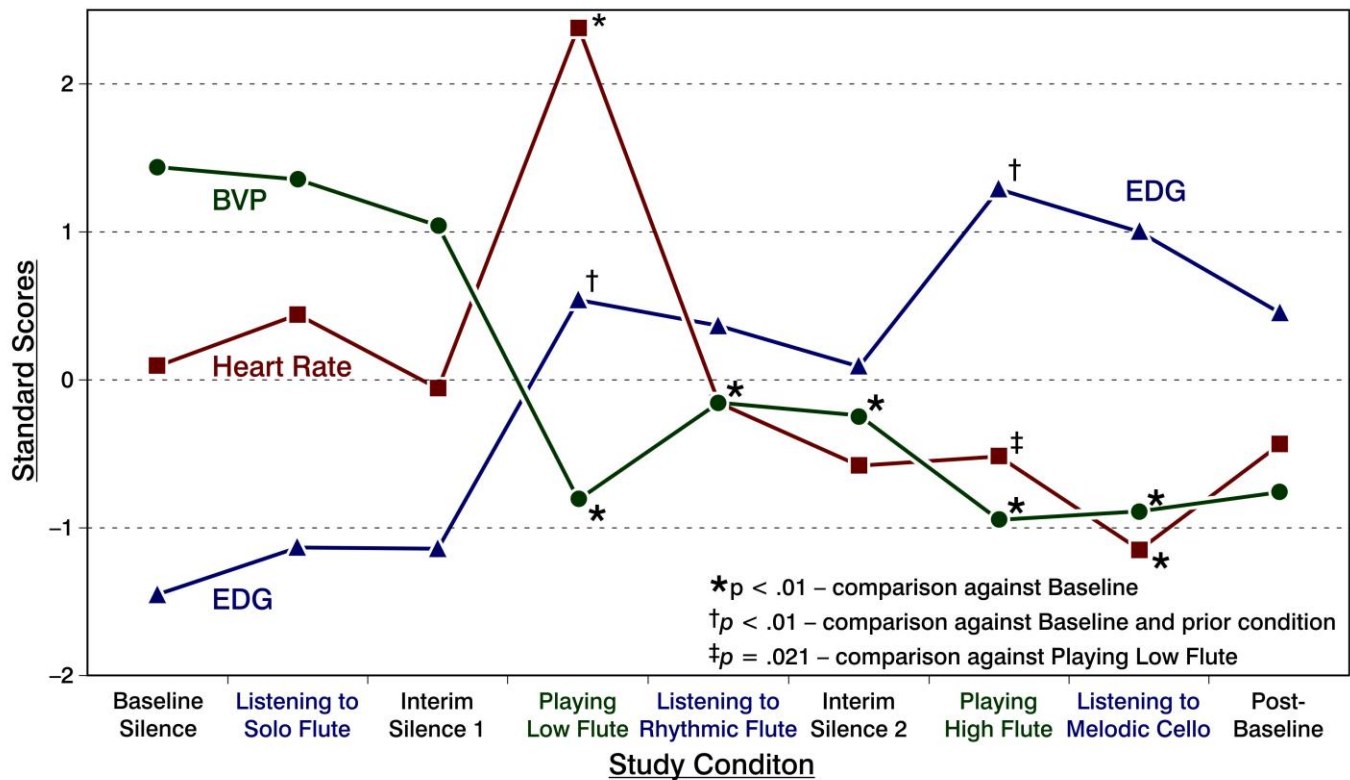


Figure 2. Autonomic measures for the full sample ($N = 15$) across all study conditions. BVP = blood volume pulse. EDG = electrodermographic readings. † indicates a significance of $p < .01$ when compared both with the baseline condition and the immediately preceding condition.

Results

For this pilot study, data analysis examined a wide range of measures and possible outcomes. Because multiple statistical inferences were considered simultaneously, the statistical measures presented should be considered exploratory.

These repeated-measures ANOVAs were calculated: theta and alpha: $F(6, 66) = 5.368, p < .001, \eta_p^2 = .328$; wide-band beta: $F(6, 66) = 3.280, p = .007, \eta_p^2 = .230$; EBC16: $F(6, 66) = 2.828, p = .016, \eta_p^2 = .205$; EBC10: $F(6, 66) = 3.159, p = .009, \eta_p^2 = .223$.

Autonomic Response

Figure 2 plots the trends in autonomic responses to the study conditions. A generally inverse relationship between BVP and EDG can be seen. This pattern helps to corroborate the validity of the measures since it would be expected that, during the passive silence and listening conditions, sympathetic nervous system activity would decrease, allowing for increased blood flow.

As expected, EDG increased from baseline to both playing lower-pitched flute ($p < .001$) and playing higher-pitched flute ($p = .001$). However, the trend of EDG in

Figure 2 shows the slow decay that is often seen when recovering from quick onset of activation (Miller, 2011).

HR increased from baseline to playing lower-pitched flute ($p < .001$). This increase in physical arousal was corroborated by a corresponding increase in EDG ($p < .001$) and a decrease in BVP from baseline to playing lower-pitched flute ($p < .001$).

Mean HR, however, decreased from baseline to playing higher-pitched flutes. HR was significantly lower when playing higher-pitched flutes than lower-pitched flutes ($p = .021$). We speculate that this may be due to an ordering effect, where playing the flute for the first time caused some anxiety that was not present in the second flute playing condition. This decrease in HR with a concurrent increase in EDG indicates differing reactions between the vagal response and the exocrine system response – a divergence that begs further investigation.

When listening to the melodic cello music, participants displayed lower HR from baseline ($p = .008$). This HR decrease did not occur in the other two listening conditions.

EEG Response

Figure 3 plots the trends in EEG response to the study conditions.

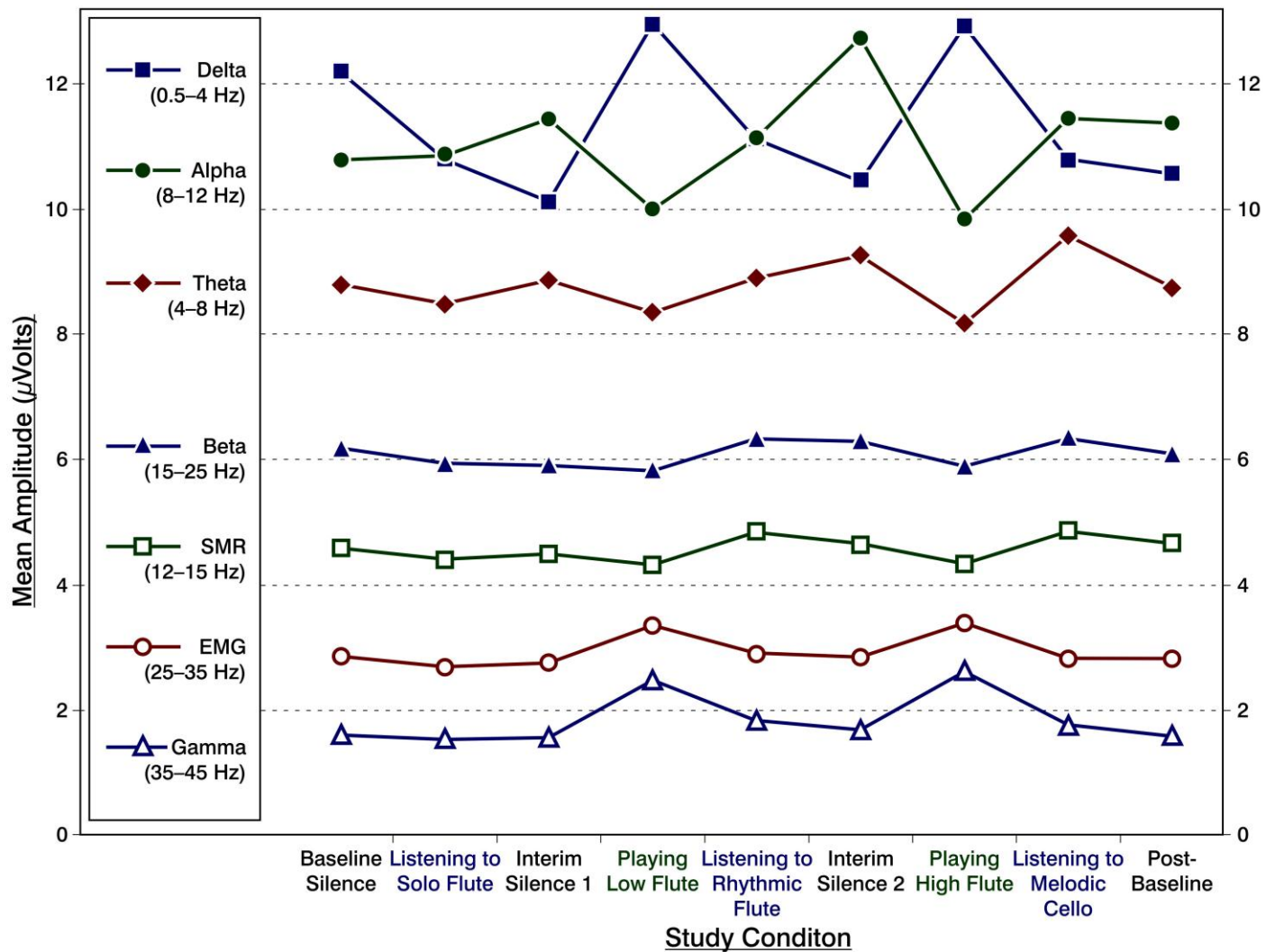


Figure 3. EEG activity for the full sample ($N = 15$) across all study conditions.

Figure 3 is remarkable for the predominantly inverse and reversible relationship between the delta and alpha bands. The general trend of the theta band follows the alpha band. However, contrary to our expectations, mean alpha band activity was reduced for both playing conditions.

Activity in the SMR and beta bands was reduced during the two flute playing conditions. While these trends were not statistically significant, the reduced activity in these bands while playing indicates that the physical movements involved with flute playing did not mask an actual decrease in alpha and theta during the flute playing conditions.

Mean delta band activity decreased from baseline for all three listening conditions. This decrease was significant for listening to melodic cello ($p = .032$) and approached significance for listening to rhythmic flute ($p = .057$).

No significant differences were found for theta band activity for the full sample across conditions as compared with baseline.

Alpha band activity was highest across the study conditions during interim silence 2 – significantly higher than the two preceding conditions, playing lower-pitched flute ($p = .006$) and listening to rhythmic flute ($p = .008$), as well as the aggregate of the listening conditions ($p = .010$) and the aggregate of the playing conditions ($p = .004$). Mean alpha band activity during interim silence 2 was also higher than during baseline silence, a result that approached significance ($p = .067$).

Figure 4 shows differences in EEG beta response among the listening conditions. When compared with listening to solo flute, beta response was significantly higher when listening to melodic cello ($p = .039$), as well as listening to rhythmic flute ($p = .029$).

We hypothesize that the rhythmic structure played a role in these significant differences, possibly indicating a reduction in mental activity and cognitive tasking while listening to music with less rhythmic structure.

Beta band activity showed no significant differences from baseline silence. However, wide-band beta response when listening to solo flute was lower than the aggregate of the silence conditions ($p = .013$).

As expected, EMG activity increased from baseline to playing lower-pitched flute ($p = .021$). We surmise that the increase in EMG resulted from the voluntary muscle movements involved in the playing conditions.

EMG increase was not significant from baseline to playing higher-pitched flute. We surmise that this was due to the tendency for higher-pitched flutes to be smaller, lighter, and to involve less finger spread. EMG from

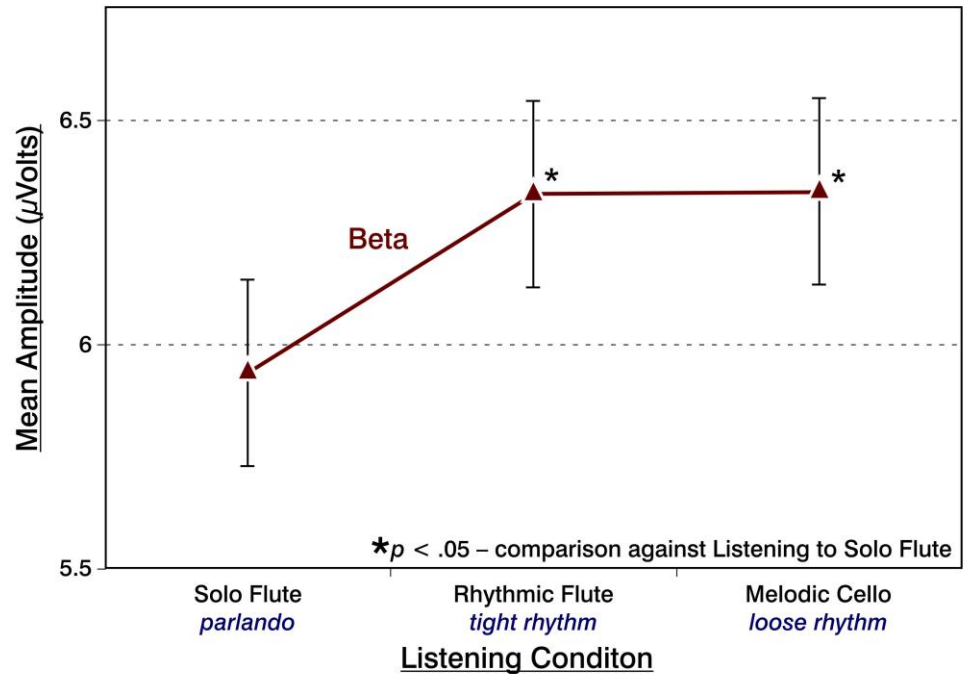


Figure 4. Beta (15–25 Hz) activity for the full sample ($N = 15$) across the listening conditions. The error bars depict ± 1 standard deviation of that EEG band across all study conditions.

Table 1. Metrics for Two Exemplary Participants showing Alpha Suppression and Enhancement

Participant Type Condition	Alpha			Alpha / Beta Ratio		
	<i>M</i>	<i>p</i> -Base	<i>p</i> -Post	<i>M</i>	<i>p</i> -Base	<i>p</i> -Post
Alpha Suppression Exemplary Participant						
Baseline	16.34		.009	3.29		.028
Playing lower-pitched flute	11.54	< .001	< .001	2.16	< .001	< .001
Playing higher-pitched flute	10.72	< .001	< .001	1.75	< .001	< .001
Post-baseline	19.09	.009		3.82	.028	
Alpha Enhancement Exemplary Participant						
Baseline	10.94		< .001	1.73		< .001
Playing lower-pitched flute	18.68	< .001	.130	2.42	< .001	.731
Playing higher-pitched flute	19.14	< .001	.053	2.54	< .001	.221
Post-baseline	16.96	< .001		2.37	< .001	

Note: Alpha band activity is in μ Volts. *p*-Base = comparison against baseline silence. *p*-Post = comparison against post-baseline silence. Single-subject Student's *t*-Tests are two-tailed heteroscedastic comparisons.

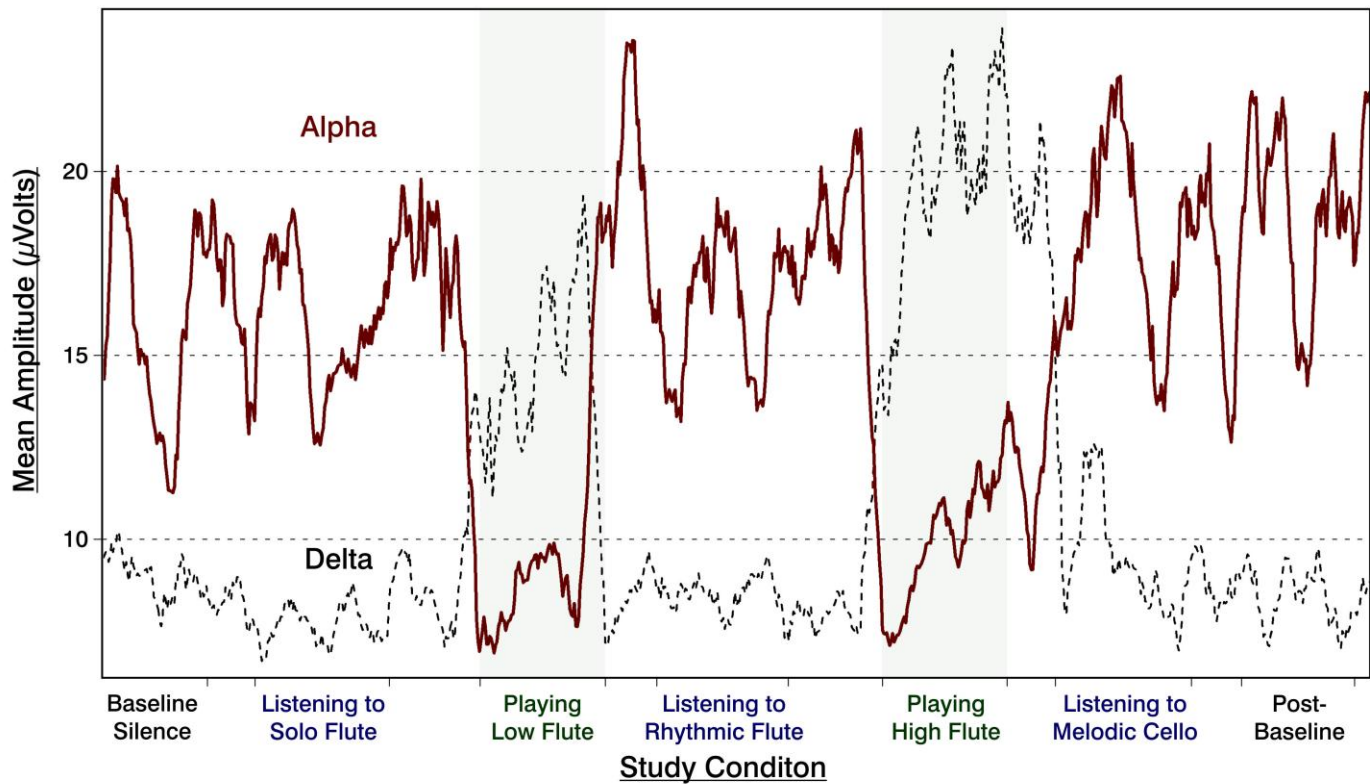


Figure 5. EEG alpha (8–12 Hz) and delta (0.5–4 Hz) activity for a participant showing alpha suppression and alpha–delta crossover.

baseline silence to all non-playing conditions shows no significant differences, with the mean EMG showing a decrease in some cases.

EEG Trends in the Novice Subgroup

The novice subgroup ($n = 7$) demonstrated some significant EEG responses to the flute playing conditions that were not evident in the full sample:

- Alpha response decreased from baseline to playing higher-pitched flute ($p = .030$) and from the prior interim silence to playing higher-pitched flute ($p = .019$).
- Theta increased from baseline to post-baseline ($p = .031$).
- Beta response decreased from baseline to both playing lower-pitched flute ($p = .036$) and playing higher-pitched flute ($p = .018$), as well as the aggregate of the two flute playing conditions ($p = .021$).

In contrast to the decrease in beta during the playing conditions seen in the novice subgroup, the experienced subgroup showed a slight increase in mean beta response from baseline to playing lower-pitched flute, playing higher-pitched flute, and the aggregate of the two flute playing conditions. This contrast may indicate a differential reduction in mental activity when playing Native American

flutes based on the level of experience with the instrument.

Alpha Suppression and Alpha Enhancement

Some individual participants showed a distinct pattern of lowered alpha band response during the flute playing conditions, while other participants showed the opposite effect of increased alpha band response during flute playing.

Figure 5 shows one participant that exemplifies the alpha suppression pattern – remarkable for the dramatic reduction in alpha activity that appeared only during the two flute playing conditions. As shown in Table 1, this participant showed significantly lower alpha as well as alpha/beta ratios when comparing lower-pitched and higher-pitched flute playing to baseline and post-baseline silence.

Table 1 also shows an exemplary participant exhibiting alpha enhancement, with significantly higher alpha and alpha/beta ratios for both lower-pitched and higher-pitched flutes when compared to baseline. In addition, significantly higher alpha activity from baseline to post-baseline was shown in both the alpha suppression and alpha enhancement exemplary participants.

Alpha Correlation with Experience Playing

To analyze correlations, we defined Δ alpha for a study condition to be the measure of alpha activity in that study condition divided by alpha activity during baseline silence.

Table 2. Trends between the First Half and the Second Half of the Listening Conditions

Metric	Listening to ...					
	Solo Flute		Rhythmic Flute		Melodic Cello	
	Δ	p	Δ	p	Δ	p
HR	-0.3%	.604	-1.1%	.210	+0.6%	.479
BVP	-8.2%	.115	+0.4%	.950	+11.4%	.297
EDG	+0.3%	.777	-2.0%	.045 *	-2.6%	.011 *
Delta	+3.5%	.334	+0.5%	.900	-9.0%	.013 *
Theta	-0.7%	.787	+2.7%	.161	-6.1%	.232
Alpha	+6.6%	.040 *	+1.6%	.651	+5.1%	.266
SMR	+5.1%	.006 *	+1.9%	.459	-0.6%	.834
Beta	-0.5%	.819	+3.0%	.223	-2.2%	.388
Gamma	+7.4%	.123	-5.3%	.328	-8.7%	.003 *
Alpha / Beta ratio	+6.7%	.020 *	-0.6%	.884	+7.5%	.035 *
Alpha / Theta ratio	+8.3%	.025 *	-2.3%	.643	+8.4%	.023 *

Note: Δ = change between the first half and the second half of the study condition. HR = heart rate. BVP = blood volume pulse. EDG = electrodermographic readings. SMR = sensorimotor rhythm. * = $p < .05$.

For the full sample, the number of years of experience reported by the participants playing Native American flutes was strongly correlated to Δ alpha for playing lower-pitched flute ($r = +.699$) and for playing higher-pitched flute ($r = +.691$), as well as the aggregate of the two flute playing conditions ($r = +.700$).

in autonomic and narrow EEG band metrics from the first half to the second half of each listening condition. In contrast with baseline silence, two listening conditions show modest, but statistically significant, decreases in EDG, suggesting a relaxing effect after initial activation of the autonomic nervous system.

Trends during Study Conditions

A number of participants demonstrated noticeable trends within various study conditions. To analyze these trends, we divided each study condition into two time periods of equal length.

Trends during baseline silence. There were no significant trends in any of the participants for HR, EDG, BVP, or EMG during the baseline silence condition. EEG activity showed no significant trends for delta, alpha, SMR, beta, or gamma. However, there was a decrease in theta activity ($p = .046$) from the first half to the second half of the baseline silence.

Trends during listening conditions. Table 2 shows changes

Table 3. Trends between the First Half and the Second Half of the Playing Conditions

Metric	Playing Lower-pitched Flute		Playing Higher-pitched Flute	
	Δ	p	Δ	p
HR	-1.3%	.446	-1.7%	.215
BVP	+26.3%	.005 *	+16.1%	.034 *
EDG	+1.0%	.514	-2.4%	.046 *
Delta	-1.9%	.696	+2.0%	.536
Theta	+8.5%	.052	+8.8%	< .001 *
Alpha	+16.7%	.009 *	+5.9%	.236
SMR	+10.0%	.002 *	+9.2%	.006 *
Beta	+7.4%	< .001 *	+9.4%	.002 *
Gamma	+0.4%	.962	+12.5%	.045 *

Note: Δ = change between the first half and the second half of the study condition. HR = heart rate. BVP = blood volume pulse. EDG = electrodermographic readings. SMR = sensorimotor rhythm. * = $p < .05$.

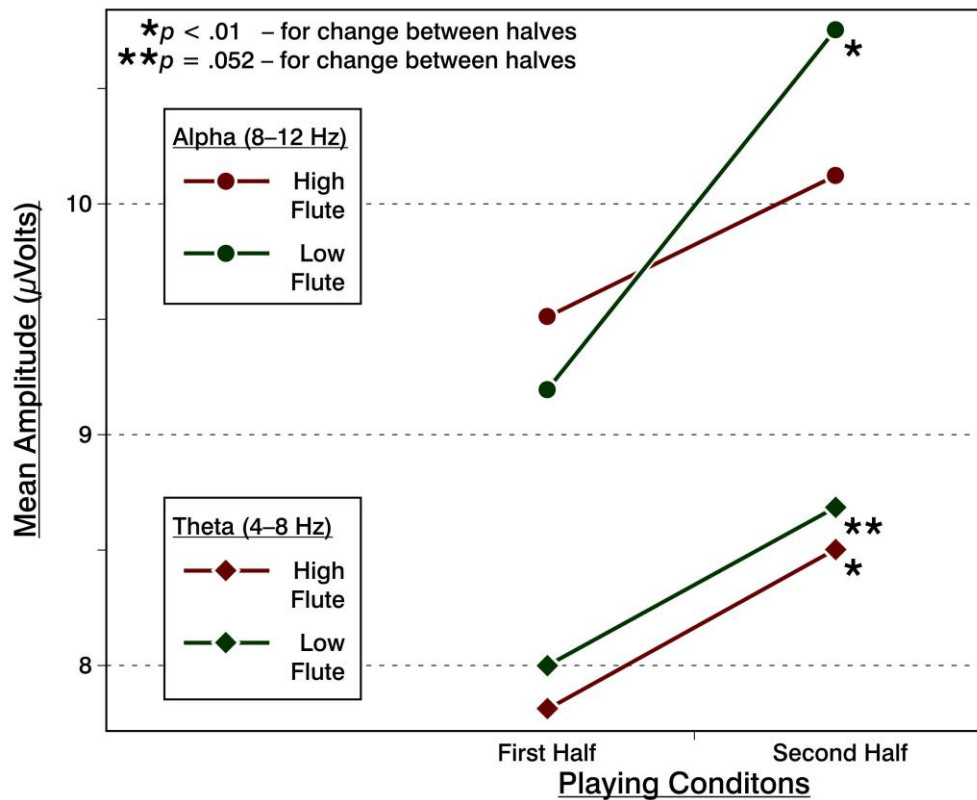


Figure 6. Alpha and Theta increase during the Native American flute playing conditions.

Table 2 also includes two notable ratios that show significant increases for two of the listening conditions. Increasing alpha relative to beta suggests a move toward a light meditative state with reduced cognitive tasking.

Trends during playing conditions. Table 3 shows changes in autonomic and narrow EEG band metrics from the first half to the second half of each playing condition.

Note the decreasing trend for EDG while playing higher-pitched flute and the significant rise in BVP and slight decrease in mean HR for both playing conditions. These trends suggest that the relaxation response, seen in two of the listening conditions above, is also evident when playing higher-pitched flute.

In the aggregate of the two flute playing conditions, Figure 6 shows a significant increase in theta ($p = .007$). Individually, theta increase is strongly

significant playing higher-pitched flute ($p < .001$) and approached significance playing lower-pitched flute ($p = .052$). Playing lower-pitched flute was accompanied by increased alpha ($p = .009$), but alpha increase for higher-pitched flute was not significant ($p = .236$).

HRV Response

Figure 7 shows the trends in the two HRV metrics across the study conditions. The two metrics exhibit a strong positive correlation ($r = +.961$).

The specifics on these HRV trends for the playing and listening conditions are shown in Table 4.

HRV increased significantly for the two flute playing conditions from the baseline silence condition. Both HRV metrics also increased for the two playing conditions from their prior interim silence conditions: interim silence 1 to playing lower-pitched

Table 4. Comparison of HRV Metrics across the Study Conditions

Condition	EBC10		EBC16	
	<i>M</i>	<i>p</i>	<i>M</i>	<i>p</i>
Baseline	1.66		1.95	
Playing ...				
Lower-pitched flute	2.66	.004 *	3.39	.003 *
Higher-pitched flute	2.94	< .001 *	3.71	< .001 *
Listening to ...				
Solo flute	1.62	.852	2.20	.351
Rhythmic flute	2.35	.082	3.22	.036 *
Melodic cello	3.15	< .001 *	4.35	< .001 *
Post-baseline	2.48	.027 *	3.33	.006 *

Note: Mean values are in beats/min. EBC16 and EBC10 are metrics of heart rate variability: the average of the differences between the maximum heart rate and the minimum heart rate within discrete consecutive windows of 16 and 10 seconds, respectively. *p* values are for comparisons against the baseline silence condition. * = $p < .05$.

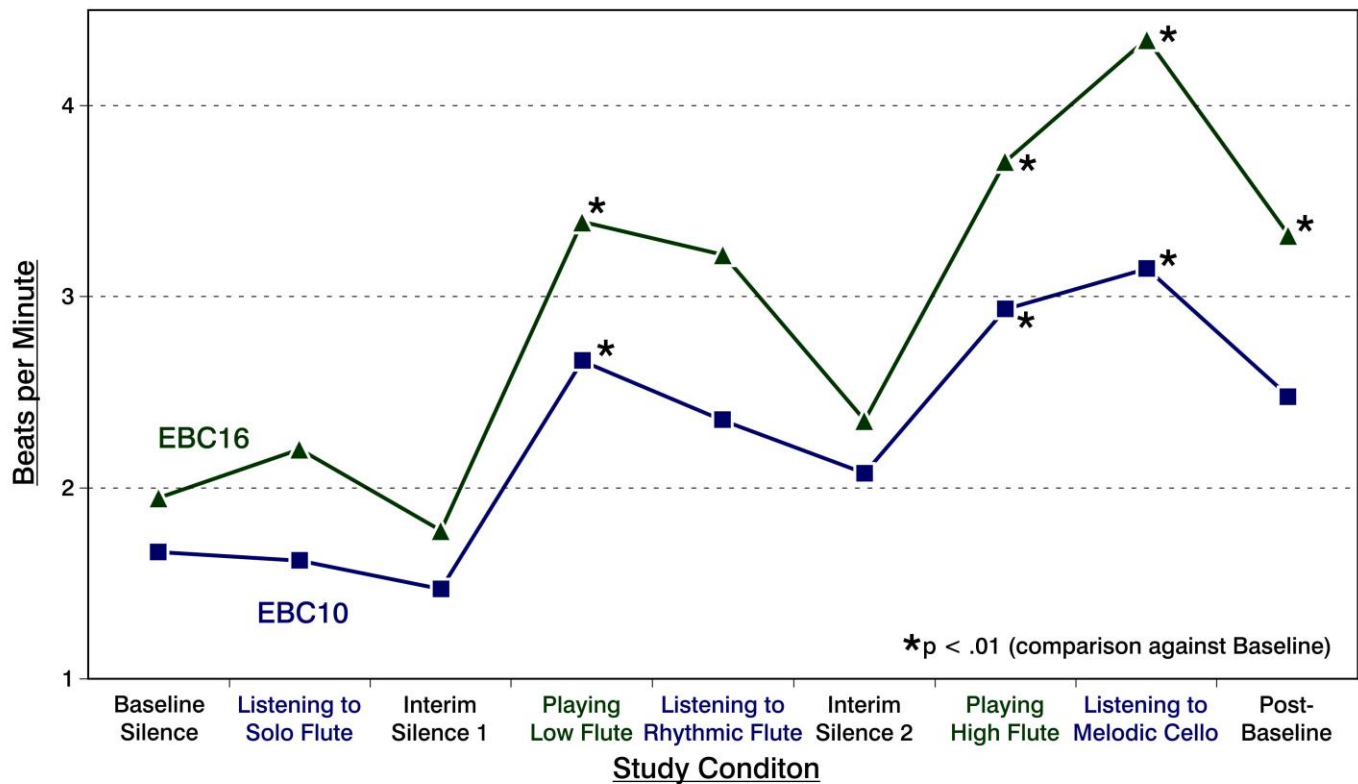


Figure 7. Heart rate variability (HRV) metrics for the full sample ($N = 15$) across all study conditions. EBC16 and EBC10 are metrics of HRV: the average of the differences between the maximum heart rate and the minimum heart rate within discrete consecutive windows of 16 and 10 seconds, respectively.

flute for EBC10 ($p = .005$) and for EBC16 ($p = .011$); interim silence 2 to playing higher-pitched flute for EBC10 ($p = .117$) and for EBC16 ($p = .044$).

Listening conditions showed significant increases in HRV metrics from baseline for EBC10 and EBC16 when listening to melodic cello ($p < .001$) and EBC16 when listening to rhythmic flute ($p = .036$). These results may have been related to an ordering effect, since these listening conditions followed playing conditions that showed increased HRV metrics. The increase in both HRV metrics carried into the post-baseline silence, with significant increases from the initial baseline silence condition. The two HRV metrics were very strongly correlated with EDG: EBC10 ($r = +.955$) and EBC16 ($r = +.917$).

To highlight changes in HRV, we define Δ HRV as the measure of HRV in a study condition divided by HRV during baseline silence, expressed as a percentage of change. Δ HRV for the aggregate of the two playing conditions is +78.4% for EBC10 and +89.4% for EBC16. The average Δ HRV for the two metrics was +80.3% ($p = .004$) for playing lower-pitched flute and +87.5% ($p < .001$) for playing higher-pitched flute. A combination of these metrics gave an average Δ HRV across the two EBC metrics and the two playing conditions of +83.9% ($p < .001$).

Δ HRV did not correlate strongly with age, gender, or experience playing Native American flutes. However, participants with less experience at meditation practices showed greater Δ HRV: for the full sample, the number of years of experience that participants reported in a meditation practice was negatively correlated to Δ EBC16 for the aggregate of the playing conditions ($r = -.612$).

Discussion

Results in Light of the Hypotheses

We established several specific hypotheses regarding listening and playing conditions that could be relevant to clinical music therapy.

Alpha and theta. With regard to our expectations of increased alpha during listening and playing conditions, we in fact found the reverse to be the case over the whole sample for flute playing and some flute listening conditions. One possible explanation is that the alpha suppression and alpha enhancement subtype patterns identified had a cancelling effect that masked alpha trends in the full sample. With individual participants showing significant alpha increase, we can envision future research aimed at determining what characteristics contribute to this pattern

(such as experience playing the flute or years of meditation practice).

Another possible factor limiting the increase of alpha could be that the time period of two minutes was not a sufficient length of time to achieve a meditative state deep enough to be discernible by EEG rhythms. Trends within the lower-pitched flute playing condition showed increasing theta ($p = .052$) and alpha ($p = .009$), while trends within the higher-pitched flute playing condition showed significantly increasing theta ($p < .001$) but not alpha.

In both cases, with the trend of increasing alpha and theta activity, a longer period of time for the flute playing condition might yield an increase in alpha and or theta sufficient to differentiate flute playing from baseline.

Beta. Our hypotheses relating to beta suppression were partially supported in this study, with significantly lower wide-band beta during listening to solo flute than the aggregate silence. Listening to solo flute was also accompanied by lower beta, as shown in Figure 4, when compared with the other two listening conditions.

Autonomic metrics. Indications of participants moving toward a relaxed state during the flute playing conditions include increases in BVP and a decrease in EDG during higher-pitched flute playing, without an increase in HR in either condition. We also note a significant decrease in HR from lower-pitched flute playing to higher-pitched flute playing.

While the slow-wave EEG metrics point toward a stronger relaxation effect for playing lower-pitched flutes, the autonomic metrics appear to indicate a stronger relaxation effect for playing higher-pitched flutes. However, we are skeptical of the implications of the autonomic metrics when considering that EDG was highest during the higher-pitched flute playing condition.

Heart Rate Variability

HRV (not to be confused with cardiac dysrhythmia) is a characteristic of healthy individuals (Wheat & Larkin, 2010). Low HRV is correlated to a number of medical and psychological diseases, such as anxiety (Friedman, 2007), hypertension (Elliot et al., 2004), chronic obstructive pulmonary disease (COPD) (Giardino, Chan, & Borson, 2004), and depression (Nahshoni et al., 2004). Low HRV is also a prognostic indicator of sudden cardiac death (Goldberger, 1991; Goldberger, Rigney, Mietus, Antman, & Greenwald, 1988).

Several studies have investigated the relationship between HRV and playing musical instruments with respect to performance anxiety (Harmat & Theorell, 2010; Harmat et al., 2011; Nakahara, Furuya, Obata, Masuko, & Kinoshita,

2009; Thurber, 2006). However, none have involved the Native American flute.

We found significant increases in HRV when playing both lower-pitched and higher-pitched Native American flutes. Biofeedback training to raise HRV focuses on breathing techniques, while receiving visual or aural representations of the immediate effects of breathing. We suggest that playing Native American flutes may have an analogous effect to the breath-training component of biofeedback training to raise HRV.

Music playing showed a stronger effect on HRV in this study than music listening. This contrasts with Nakahara, Furuya, Francis, & Kinoshita (2010), who report a decrease in the RMSSD measure of HRV (the root mean square of the successive differences between adjacent R–R intervals from normalized ECG data) from resting to performance by elite pianists during solo performance. Although HRV was highest during the final listening condition, this could have been due to an ordering effect, since it immediately followed playing higher-pitched flute.

Clinical Implications for Music Therapy

The finding of increased HRV during the flute playing conditions indicates the potential for use of the Native American flute in treatment of a range of clinical conditions that a music therapist might encounter. Biofeedback training to raise HRV has been found to have various degrees of effectiveness in the treatment of asthma (Lehrer et al., 1997, 2004), hypertension (Elliot et al., 2004), anxiety (Henriques, Keffer, Abrahamson, & Horst, 2011), COPD (Giardino, Chan, & Borson, 2004), post-traumatic stress disorder (PTSD) (Zucker, Samuelson, Muench, Greenberg, & Gevirtz, 2009), and recurrent abdominal pain (Sowder, Gevirtz, Shapiro, & Ebert, 2010). In the treatment of major depressive disorder, biofeedback training to raise HRV demonstrated effects that appeared stronger than most selective serotonin reuptake inhibitors, suggesting that this approach may provide a non-pharmacological alternative treatment method (Karavidas, 2008; Karavidas et al., 2007).

In a review of the literature on biofeedback training to raise HRV, Wheat and Larkin (2010) opined:

Significant improvements in clinical outcomes were overwhelmingly evident in the reviewed literature. This is particularly notable given that such changes cut across several disease states ... Therefore, HRV BF should be considered seriously as a viable avenue through which to supplement traditional treatments of various illnesses. (p. 237)

The broad range of applicability of biofeedback training

to increase HRV (Wheat & Larkin, 2010) raises a key question for further investigation: Could playing Native American flute prove efficacious for some of these clinical conditions?

We also note that the integration of mental and respiratory functions is central to many Eastern meditation practices, such as Yoga, Qigong, and Zen (Lehrer, Vaschillo, & Vaschillo, 2000). A central tenet that the mind and breathing are interdependent is embodied in the writings of Yue Yanggui: “*the tranquility of the mind regulates the breathing naturally and, in turn, regulated breathing brings on concentration of the mind naturally*” (Meihua Wen Da Plan [Questions and Answers of Meihua], cited in Xiangcai, 2000, p. 7).

Limitations of the Present Study

The sample size of this pilot study may not have been sufficient to distinguish statistical differences in some of the interesting trends.

The convenience sample of participants ranged in age from 52 to 70 years, with a mean age of 58.4 years. This age bracket is more likely to yield lower HRV readings than a younger population (Moss, 2004; Sandercock et al., 2005).

Playing style during the two playing conditions was not recorded. Players may take full breaths between long passages, shallow breaths for short passages and rhythmic melodies, or even engage in *circular breathing*, which allows continuous playing using small, frequent inhalations through the nose. Although not formally documented, no circular breathing was observed by the investigators. Controlling for a full range of playing styles in future studies is warranted.

The finger sensor may have been bothersome to some participants during the playing conditions. The sensor was placed on the fifth digit of the hand closest to the foot end of the flute – a finger that is not normally used in covering the finger holes of the instrument. However, some players position that finger on the barrel of the instrument for stability. A possible alternative might be to explore the use of ear or toe sensors (Allen, 2007).

The single-sensor EEG interface lacked the ability to localize brain waves. The results could possibly have been more discriminating if a qEEG topographical brain map was employed.

Future analysis could run EEG data through cleaning algorithms, such as those implemented in NeuroGuide software (Thatcher, 2008), to determine if results are consistent.

Distinguishing myogenic from neurogenic signal sources in scalp recordings of high-frequency EEG is known to be

problematic (Whitham et al., 2008). Goncharova, McFarland, Vaughan, & Wolpaw (2003) reports a broad frequency distribution of EMG from 0 Hz to greater than 200 Hz with highest amplitudes frontally in the range of 20–30 Hz. Even weak EMG is detectable in scalp recordings in frequencies down into the 8–13 Hz range in some individuals (Shackman et al., 2009).

The time for each study condition – approximately two minutes – is below the recommended five-minute period recommended for the reliable calculation of SDNN metrics for HRV (Task Force, 1996). However, as noted in Berntson et al. (1997), it may not be possible to maintain a stable psychological or cognitive state over a period of five minutes. In any case, it is appropriate to compare SDNN in different periods only if the durations for those study periods are the same (Task Force, 1996).

Although we did not measure breathing frequency of participants during this study, we can infer that the length of an average breath cycle lengthens when playing flute from the normal respiratory cycle of 3–5 seconds in adults (Lindh, Pooler, Tamparo, & Dahl, 2009) to approximately 10 seconds – the mean reported breath cycle in the informal breathing-rate survey. This closely matches the breath cycle of approximately 10 seconds in paced breathing that produces the maximal increases in HRV during biofeedback training to raise HRV (Vaschillo, Vaschillo, & Lehrer, 2006).

While aggregating the silent periods provided a solution in this study, longer periods of silence would allow for stronger comparative analyses.

We did not control for the level of intraoral breath pressure that participants produced, nor the breath volume required during the playing conditions. Breath pressure and breath volume are affected by the resistance provided by the particular instrument, as well as the volume of the sound produced (Goss, 2013).

In this study, participants played their own personal flutes, which increased the variability of breath pressure and breath volume.

No data was collected on the medical conditions, prescribed medications, or other health-related attributes of the participants. In this study, the use of a baseline design controls for the potential effects of medications on EEG measurements across conditions, since we are looking at relative changes from baseline to other study conditions and within condition trends.

Likewise, we did not collect data on the musical preferences of the participants. This could have provided insight into how musical preferences of, for example,

parlando style versus rhythmic style, correlate with the physiological responses to listening and playing.

Finally, this study did not control for the sequence of playing and listening conditions that may have contributed to ordering effects.

Conclusions and Directions for Future Studies

This study was prompted by a concordance of factors suggesting that playing the Native American flute and/or listening to Native American flute music may effect a variety of psychological changes with the potential for use in treating clinical conditions in a music therapy context. These factors include: the cultural traditions surrounding the role of the instrument in healing, prior studies and anecdotal evidence of the effectiveness of various wind instruments for a range of clinical conditions, and the widespread availability and increasing use of the instrument in present society. Despite the limitations noted, this study provides an initial investigation of the effects of the Native American flute based on physiological measurements.

While we found some results that support our hypotheses regarding physiological responses to playing and listening to Native American flutes, we have also raised a host of questions. In addition to the specific improvements in study design implied by the Limitations section above and the general directions suggested in the prior Clinical Implications for Music Therapy section, we offer this list of potential questions and directions for future research studies:

- Can differing subtypes based on alpha band response to the flute playing conditions be confirmed and, if so, do they correlate to other factors?
- Are the effects observed in the present study also found in other wind instruments, particularly wind instruments that are outside the domain of orchestral wind instruments that have been the subject of the majority of research studies on wind instruments?
- Can the differing reactions between the vagal response and the exocrine system response implied by our finding of decreased HR with concurrent increased EDG in the playing higher-pitched flute condition be confirmed and, if so, correlated to other factors?

Considering the increased HRV during flute playing found in this study, and the previously demonstrated effect of biofeedback training to raise HRV on a range of clinical conditions, we suggest that the most compelling direction for future research would be a direct investigation of the effect of a music therapy program of Native American flute playing for clinical conditions, such as asthma, COPD, PTSD, recurrent abdominal pain, hypertension, anxiety, fibromyalgia, and major depressive disorder.

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Trends in Physiological Metrics during Native American Flute Playing

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ABSTRACT

This letter reports on specific physiological trends that were found during periods of playing Native American flutes for several autonomic and EEG measures. A slight downward trend in mean heart rate from 72.76 to 71.69 BPM accompanied by a significant increase in blood volume pulse ($p < .001$) suggests vasodilation, possibly indicating reduced autonomic arousal. EEG results show significant increases in theta (4–8 Hz, $p < .001$) and alpha (8–12 Hz, $p = .005$) bandwidths during flute playing. Alpha enhancement may indicate increased relaxation conducive to a meditative state. Displayed in graphical chart form are standard scores for percent change between the first half and second half of Native American flute playing conditions. These physiological trends while playing Native American flutes, taken together, suggest the possibility of a relaxation response.

Letter to the Editor

This letter reports on specific trends that were found during periods of playing Native American flutes for several autonomic and EEG measures.

The Native American flute is an ethnic wind instrument that was developed by indigenous North American cultures. It has become popular in contemporary society, in part, for its purported meditative qualities. The instrument has historically been used in ceremonial contexts, played in courtship, and used as work songs and in healing contexts.

It is presently found in museum shops, New Age gift stores and in social gatherings known as *flute circles*, where players with little formal music training are supported in community music-making (Goss, 2014).

We were able to locate a very limited number of literature references for the use of the Native American flute in music therapy settings – one dissertation study in which anxiety was reduced in individuals diagnosed with a trauma-related disorder per self-reported measures (Wiand, 2006), one instance of a music therapist using the Native American flute with a Navajo

woman in hospice (Metzger, 2006), and a newspaper story in the November 7, 2005 *New York Daily News* mentioning a Native American flute on the instrument shelf of a prominent New York music therapist. However, a keyword search for the combination “Music Therapy” and “Native American Flute” in the *PsychInfo* and *PubMed* databases yielded no results, demonstrating a paucity of scientific investigation of the physiological mechanisms underlying traditional uses of these instruments for healing.

To identify potential areas and methodologies for further physiological inquiry, we conducted an exploratory pilot investigation at the Flute Haven Native Flute School with a convenience sample of 15 volunteer Native American flute players. Participants signed an informed consent and agreed to participate in and of their own free will with an understanding that they could withdraw at any time. Participants, who varied in gender and experience playing Native American flutes, were monitored for autonomic measures via an infrared photoplethysmograph finger sensor and EEG by a monopolar sensor placed at Cz.

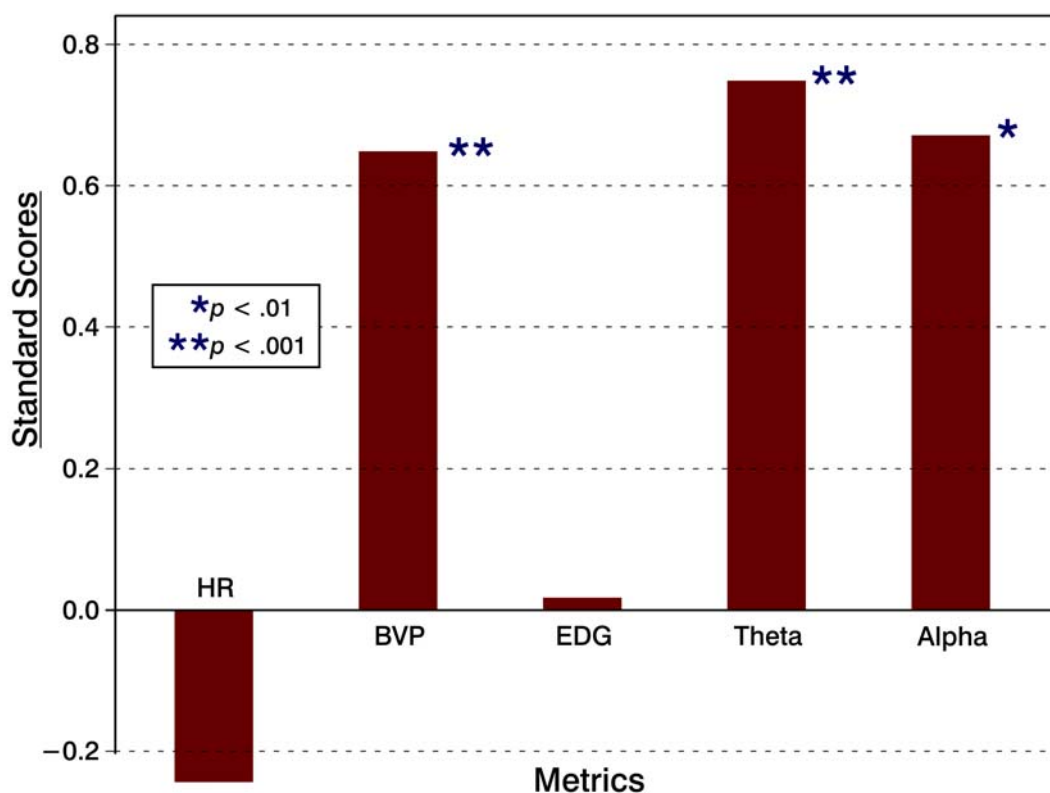


Figure 1. Physiological changes during Native American flute playing. Standard scores for percent change between the first half and second half of Native American flute playing conditions for heart rate (HR), blood volume pulse (BVP), electrodermal activity (EDG), and electroencephalograph frequency bands theta (4–8 Hz) and alpha (8–12 Hz).

We analyzed trends by comparing the first half vs. the second half of Native American flute playing conditions. Figure 1 shows a slight downward trend in mean heart rate from 72.76 to 71.69 BPM and little change in electrodermal activity (EDG), suggesting no increase in autonomic arousal. The significant increase in blood volume pulse ($p < .001$) suggests vasodilation, possibly indicating a reduction in autonomic arousal (Peper, Harvey, Lin, Tylova, & Moss, 2007).

EEG results show significant increases in theta (4–8 Hz, $p < .001$) and alpha (8–12 Hz, $p = .005$) during flute playing. Increase in alpha may be interpreted as a reduction in cognitive activity, as per the classic view that increased alpha rhythms represent a cortical idling state (Bazanov & Vernon, 2013). Alpha and slow-wave enhancement may provide markers of relaxation or meditative states.

These trends, taken together, suggest the possibility of a relaxation response. We suggest further research with larger samples and more refined measures to investigate potential physiological effects of the Native American flute for use in music therapy.

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Intraoral Pressure in Ethnic Wind Instruments



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Intraoral Pressure in Ethnic Wind Instruments

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ABSTRACT

High intraoral pressure generated when playing some wind instruments has been linked to a variety of health issues. Prior research has focused on Western classical instruments, but no work has been published on ethnic wind instruments. This study measured intraoral pressure when playing six classes of ethnic wind instruments ($N = 149$): Native American flutes ($n = 71$) and smaller samples of ethnic duct flutes, reed instruments, reedpipes, overtone whistles, and overtone flutes. Results are presented in the context of a survey of prior studies, providing a composite view of the intraoral pressure requirements of a broad range of wind instruments. Mean intraoral pressure was 8.37 mBar across all ethnic wind instruments and 5.21 ± 2.16 mBar for Native American flutes. The range of pressure in Native American flutes closely matches pressure reported in other studies for normal speech, and the maximum intraoral pressure, 20.55 mBar, is below the highest subglottal pressure reported in other studies during singing. Results show that ethnic wind instruments, with the exception of ethnic reed instruments, have generally lower intraoral pressure requirements than Western classical wind instruments. This implies a lower risk of the health issues related to high intraoral pressure.

Introduction

Intraoral pressure is an important physiological metric related to playing wind instruments. The range of intraoral pressure generated when playing an instrument is dependent on the instrument. Within that range, players alter their breath pressure to control the volume, pitch, and tone produced by the instrument.

Intraoral pressure is a consideration when choosing a wind instrument to play. Wind instruments with high intraoral pressure requirements have been linked to a number of health issues, in particular:

- Velopharyngeal incompetency (VPI), a condition where the soft palate or pharyngeal walls fail to separate the nasal cavity from the oral cavity ([Weber-J 1970], [Dibbell 1979], [Dalston 1988], [Ingrams 2000], [Schwab 2004], [Stasney 2003], [Malick 2007], [Kreuter 2008], [Evans-A 2009], [Evans-A 2010], [Evans-A 2011]).

- Pneumoparotid, where the parotid gland becomes enlarged due to air insufflation ([Kirsch 1999], [Kreuter 2008], [Lee-GG 2012]).
- Hemoptysis ([Kreuter 2008]).
- Increased intraocular pressure and intermittent high-pressure glaucoma ([Schuman 2000], [Schmidtman 2011]).
- Hypertension (possibly — see [Dimsdale 1995] and [Larger 1996]).
- Barotrauma causing reduced pulmonary function ([Deniz 2006]).
- Laryngocoele, a congenital lung condition seen in glassblowers due to high intraoral pressure ([Kreuter 2008]). [Lee-GG 2012] reports intraoral pressure as high as 200 mBar for glassblowing.

Given the range and severity of these potential health issues, preference for wind instruments with lower intraoral pressure requirements is prudent.

Citation for this article: Goss C. 2013. Intraoral pressure in ethnic wind instruments. *Flutopedia*:
http://www.Flutopedia.com/breath_pressure.htm. August 21, 2013. 16 pages. Retrieved [Your Date of Retrieval].

Intraoral pressure has been studied in speech, singing, and playing various wind instruments of the Western classical tradition. However, no studies measuring intraoral pressure in ethnic wind instruments have been reported in the literature.

This study was undertaken to determine the intraoral pressure involved in playing a wide range of ethnic wind instruments. Measurements were made on 149 ethnic wind instruments in situations that approximate normal as well as extreme playing techniques. The results are combined with intraoral and subglottal pressure measurements of speech, singing, and other instruments from prior studies in a set of charts that provide a composite view of the intraoral pressure requirements for a broad range of wind instruments. Data tables are also provided for all pressure measurements from this study as well as prior studies.

Method

Musical Instruments

Six classes of instruments were studied¹:

Native American flutes ($n = 71$): A front-held flute that has an external block and an internal wall that separates an air chamber from a resonating chamber that contains open finger holes ([Goss 2011]). Hornbostel–Sachs (HS) class 421.211.12 and 421.221.12 — edge-blown aerophones, with breath directed through an external or internal duct against an edge, with finger holes. Native American flutes used in this study were crafted by 32 different flute makers. These flutes play primarily in the first register, with some flutes having a few notes in the second register. Range is typically limited to 12–15 semitones.

Ethnic duct flutes ($n = 46$). HS class 421.221.12 — edge-blown aerophones, with breath directed through an external or internal duct against an edge, with finger holes. Typical play on these instruments is done in the first register, with normal play extending to several notes in the second register and possibly one note in the third register (sounding a major twelfth). Ethnic duct flutes in this study include the Irish whistle, Slovakian pistalka (píšťalka), Ukrainian and Russian sopilkas (Сопілка, Сопел), Romanian frula, Indonesian suling, Georgian salamuri (სალამური), Bolivian tarka, Mesoamerican clay flutes, flutes characteristic of the Tarahumara culture, and Russian sivril.

Ethnic reed instruments ($n = 4$). HS class 422.1 and 422.2 — reed aerophones, with breath directed against one or

two lamellae (reeds) which vibrate and set the air in a resonating chamber in motion. They are limited to play in one register and typically have a limited range of no more than 14 semitones. Ethnic reed instruments measured in this study comprise a Russian jaleika, an Armenian duduk (Դուդուկ), a Kenyan bung'o, and a bamboo saxophone.

Ethnic reedpipes ($n = 12$). HS class 422.31 and 422.32 — reed aerophones, single or double reedpipe with a free reed that vibrates through/at a closely fitted frame, with finger holes. They are limited to play in one register and typically have a limited range of no more than 14 semitones. Note that pitch on these instruments often responds inversely to ethnic duct flutes — decreasing as breath pressure is increased. Ethnic reedpipes measured in study comprise the Chinese bawu (巴烏), Chinese hulusi (葫蘆絲), and Laotian kaen or khene (ແຄ່ງ).

Ethnic overtone whistles ($n = 8$). HS class 421.221.12 — edge-blown aerophones, with breath directed through an internal duct against an edge, without finger holes. Due to the lack of finger holes, they have a fixed-length resonating chamber. They are designed to play high into the overtone series — sometimes as high as the tenth register. To accomplish this, they tend to have relatively long resonating chambers compared with their diameter. Ethnic overtone whistles measured in this study include the Slovakian koncovka, Norwegian willow flute (seljefløyta), and an overtone flute of the North American Choctaw culture.

Ethnic overtone flutes ($n = 8$). HS class 421.221.12. These flutes share some of the characteristics of ethnic duct flutes and ethnic overtone flutes: they have a limited number of finger holes (typically three or four) and are designed to play high into the overtone series. Ethnic overtone flutes measured in this study include the Slovakian fujara, tabor pipe, and flutes of the North American Papago and Pima cultures.

Measurement

Intraoral pressure was measured using a system constructed of components supplied by Omega Engineering (Stamford, CT). The setup consisted of:

- Meter: one DP25B-S strain meter.
- Sensor: one PX26-001DV piezoresistive pressure sensor, designed for wet conditions. It provides a differential voltage proportional to the pressure applied, in the range of 0–1 PSI.
- One CX136-4 wiring harness.
- Tubing: Clear plastic flexible tubing, 5/16" outside diameter, 3/16" inside diameter (55" for measurements, 128" for water-column calibration).

¹ In some cases, instruments are identified with the culture that initiated the design of the instrument, or the predominant culture where the instrument is presently found. These are provided solely for the purpose of identifying the instrument.

The meter was configured with settings provided by Omega engineering to provide readings in the range 0.001 – 1.000 PSI in thousandths of a PSI. Based on the combined specifications of the sensor and the meter, the factory calibration of the system should be within $\pm 2.20\%$. This was confirmed by calibrating the unit against the differential height of columns of water in an extended section of tubing, at four pressure points. The greatest deviation was $+2.05\%$.

All readings were converted to milliBars (mBar), including readings from cited sources that are given in a wide variety of units, including cm H₂O, in H₂O, mm HG, kPa, and psi.



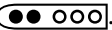


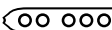

Procedures

All measurements were taken at 72 °F on instruments that were fully acclimated to that ambient room temperature. Movable parts of an instrument were adjusted to their typical or recommended playing position. Each instrument was warmed up using two long breaths into the finger holes.

The open end of the tubing, cut square, was placed in the mouth perpendicular to the general airflow while the musical instrument was played.

The procedure varied depending on the class of instrument:

Native American flutes. Nine measurements were attempted for each flute, three measurements on each of three notes:


- The root note, typically fingered 
- The fifth note, seven semitones above the root note, typically fingered  or . For flutes tuned to the diatonic major scale, the  fingering was typically used.
- The octave note, typically fingered  or . For flutes tuned to the diatonic major scale, the fingering  was typically used.

These three notes were played at three dynamics (volumes) by varying breath pressure: *forte* (*f*), *mezzo-forte* (*mf*), and *piano* (*p*). Rather than attempting to produce these dynamics subjectively, a Korg OT-120 pitch meter was used, set to A=440 Hz, equal temperament. A reference pitch (RP) for each note was established based on an “on-pitch” indication on the pitch meter. In the case of instruments that were not tuned to concert pitch, the RP was established using a breath pressure that subjectively produced a good tone.

Pressure readings for *mf* were taken after establishing a steady tone, with no vibrato, that produced the RP. Readings for *f* and *p* were taken with breath pressure that produced readings of 30 cents above and below the RP, respectively. The readings do not show effects of any articulation at the start of the note.

In some cases, it was not possible to produce all nine combinations of pitches and dynamics. For example, increasing breath pressure above *mf* on the root note on some flutes causes the flute to jump into the next register. On some diatonic flutes, readings were not possible when attempting to play *p* on the octave note, since the flute could not maintain resonance in the second register at lower breath pressure.

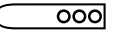

Repeatability was evaluated by replicating measurements on three flutes on three separate days. The average Coefficient of Variation (CV) was 7.5% with the maximum CV of 11.1%.

Ethnic duct flutes. Measurements were taken as with Native American flutes. Most of these flutes use the fingering  to produce the octave not in the second register. In addition, the fundamental note in each of the higher registers was attempted, as high as was possible on the instrument. Pressure measurements in these higher overtone registers were taken by establishing the pitch and then reducing breath pressure slightly to a point where the tone was stable — reference to precise tuning was not used in these higher overtone registers.

Ethnic reed instruments. Measurements were taken as with Native American flutes, except that measurements were taken only for the *mf* dynamic.

Ethnic reedpipes. Measurements were taken as with Native American flutes, but it was only possible to use breath pressure to bend pitch ± 30 cents on one instrument. Therefore, most measurements were taken at the *mf* dynamic.

Ethnic overtone whistles. One pressure measurement was taken for each note in each register by establishing the pitch and then reducing breath pressure slightly to a point where the tone was stable — reference to precise tuning was not used for this class of instruments.

Ethnic overtone flutes. Measurements were taken as with ethnic duct flutes, except that the measurement for the fifth note was taken using the fingering  or  in the first register, regardless of what pitch was produced.

Literature Survey

A literature search was done for published articles involving intraoral and subglottal measurements in musical instruments, speech, and singing. Pressure measurements from various sources were obtained from numerical data, if published, or by physically interpolating the location of charted data points. This included linear interpolation as well as non-linear interpolation in some cases where graphs used a logarithmic scale. All data points were converted to mBar.

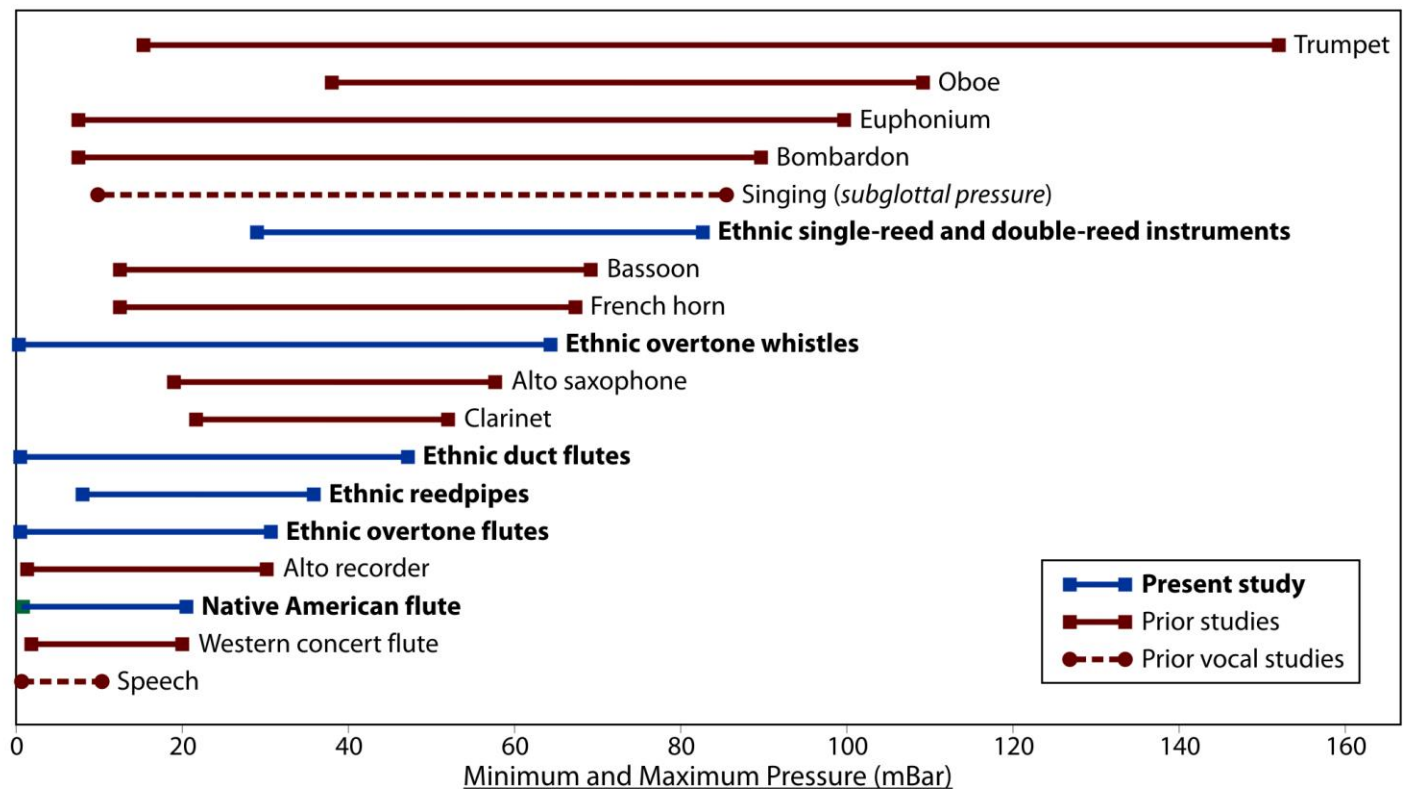


Figure 1. Summary of intraoral pressure ranges in wind instruments. The horizontal axis plots the minimum and maximum intraoral pressure for each instrument or instrument class. Measurements from this study are combined with results reported in the literature cited in Tables 1 and 2 contained in the Appendix.

Results

The composite pressure (CP) for a given instrument is the mean of all measurements for that instrument, including measurements at the various pitches and dynamics that were attainable. The mean intraoral pressure for a group of instruments is the mean of the CP values for the instruments in that group.²

The mean intraoral pressure of all ethnic wind instruments in this study was 8.37. Because the CP values across the range of instruments in this study do not show an normal distribution, no standard deviation is reported.³

Figure 1 provides an overview of the minimum and maximum intraoral pressure for each instrument or class of instruments, including measurements from this study and a survey of available literature. See Tables 1 and 2 in the Appendix for the source of all data points from prior studies.

² This approach to the analysis was taken – rather than simply averaging all measurements from the group of instruments – since: (a) different instruments contributed different numbers of measurements (because of the limitations of some instruments as noted in the [Procedures](#) section) and (b) because the coefficients of variation of measurements for a given flute were reasonably low – averaging 54.3%.

³ The standard deviation of the CP values for all instruments calculated by traditional methods is ± 8.58 mBar.

Subsequent figures plot pitch on the horizontal axis, grouped into half-octave ranges. For example: C_3 – F_3 , $F^\#_3$ – B_3 , ..., C_6 – F_6 , and $F^\#_6$ – B_6 with data points plotted at D and $G^\#$ within each range. The exception is a single measurement at the bottom of the set of half-octave ranges. In that case, the data point is plotted at the actual concert pitch for that measurement.

Intraoral pressure measured on Native American flutes ranged from a minimum of 0.83 mBar to a maximum of 20.55 mBar. The mean intraoral pressure across all Native American flutes was 5.21 ± 2.16 mBar. Because of limitations on some flutes noted previously, of the 639 possible combinations of pitches and dynamics on 71 flutes, 605 actual measurements were taken.

Figure 2 charts the mean intraoral pressure at the *f* dynamic (+30 cents) and the *p* dynamic (–30 cents), as well as the maximum and minimum of measurements at those dynamics, respectively. See Table 3 in the Appendix for all data values plotted on Figure 2.

Figure 3 places the average *f* and *p* results for Native American flutes in the context of intraoral and subglottal pressure measurements for speech that have been reported in prior studies.

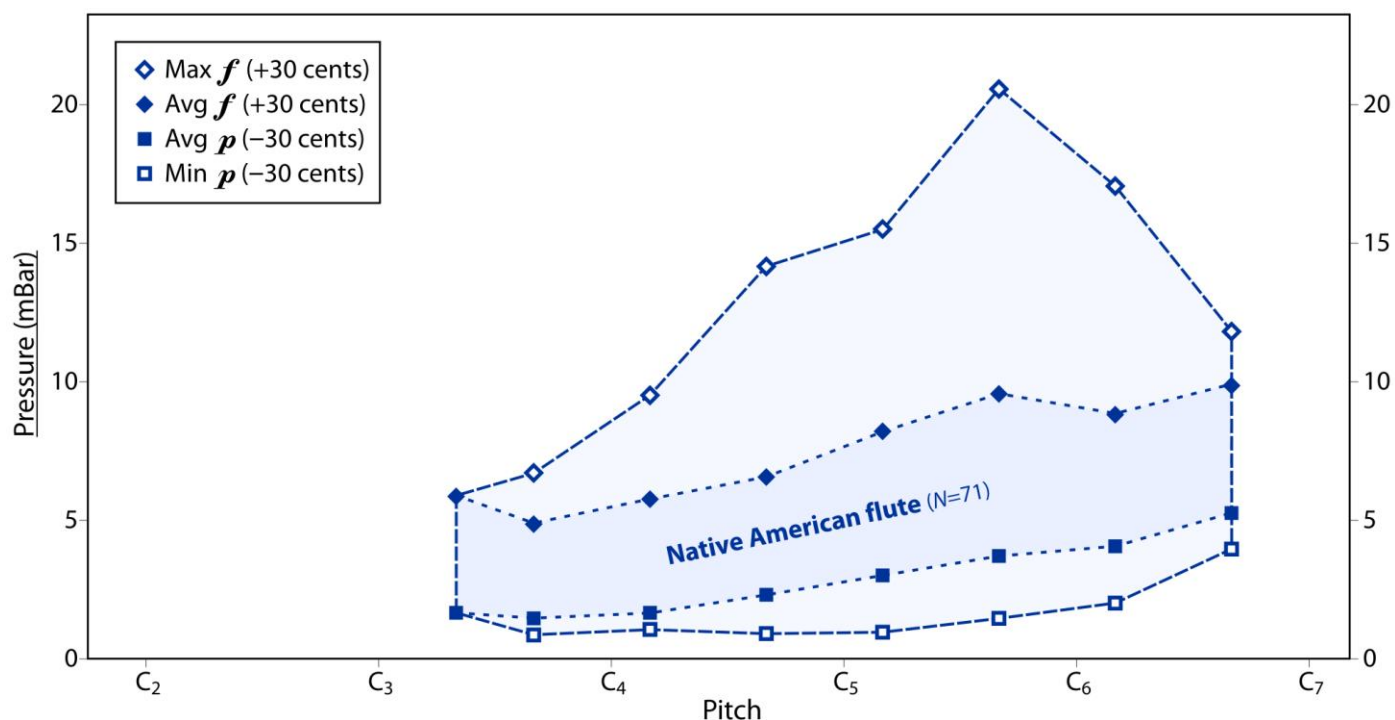


Figure 2. Native American flute – intraoral pressure. Pitches are grouped into half-octave ranges, except for the single low measurement taken at E₃. f = *forte*, measured at reference pitch (RP) + 30 cents. p = *piano*, measured at RP – 30 cents. RP is concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone.

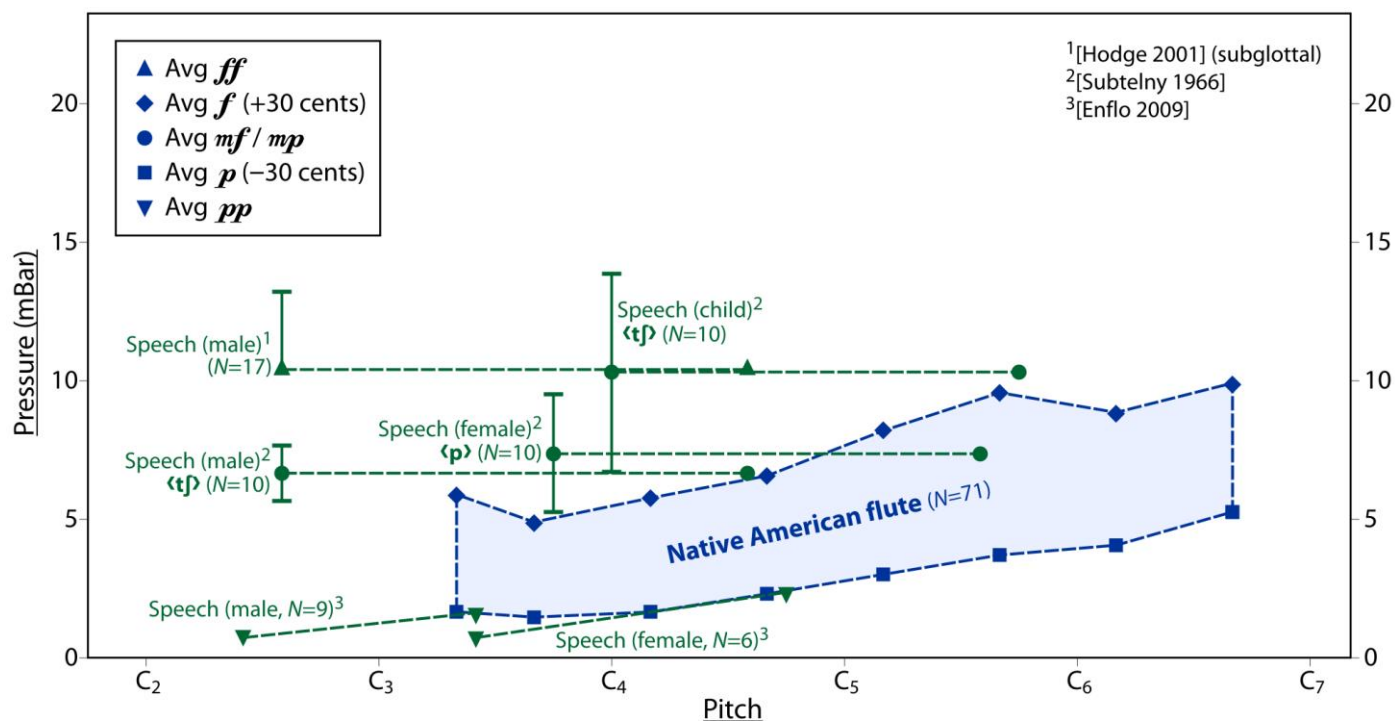


Figure 3. Speech and Native American flutes – intraoral pressure. Pitches for Native American flutes are grouped into half-octave ranges, except for the single low measurement taken at E₃. f = *forte*, measured at reference pitch (RP) + 30 cents. p = *piano*, measured at RP – 30 cents. RP is concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone. ff (*fortissimo*), pp (*pianissimo*), and mf / mp (*mezzo-forte / mezzo-piano*) are general indications of dynamics that are defined specifically in each of the cited references. The error bars for speech represent one standard deviation.

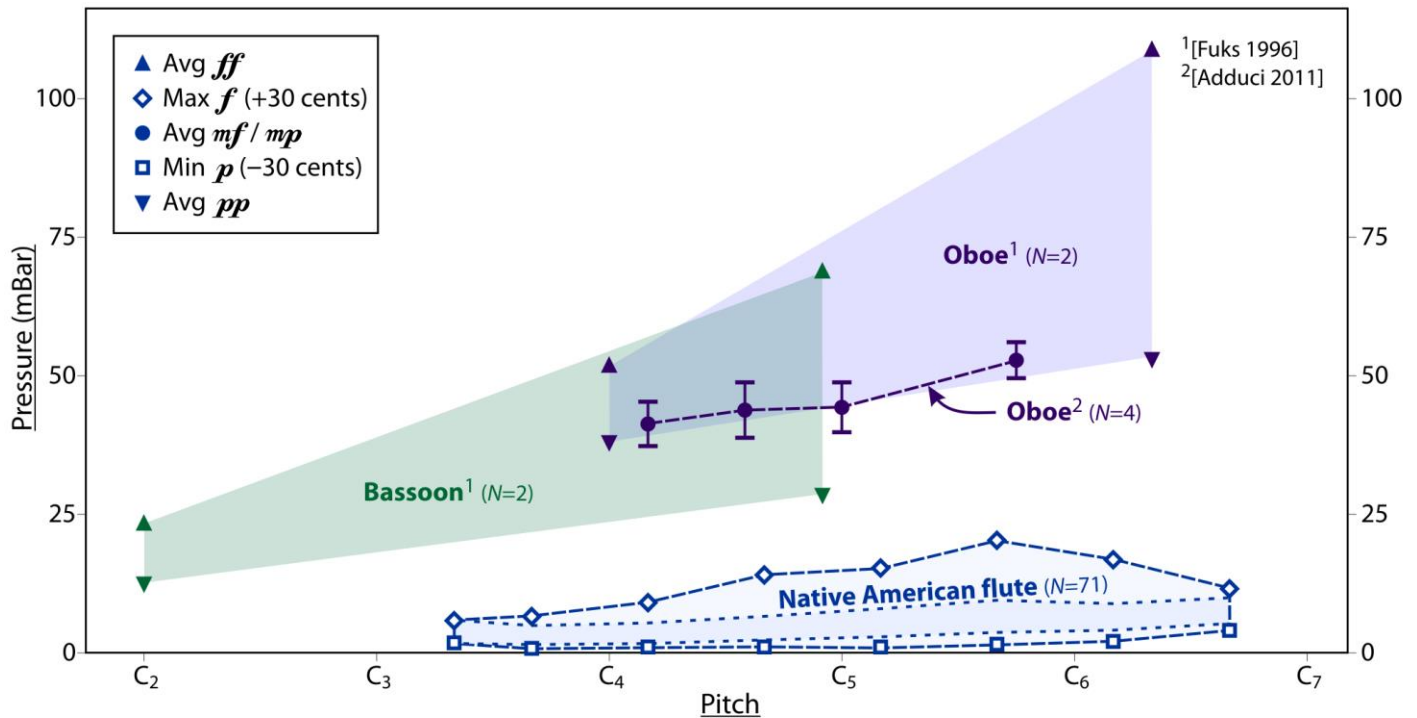


Figure 4. Double-reed instruments and Native American flute – intraoral pressure. Pitches for Native American flutes are grouped into half-octave ranges, except for the single low measurement taken at E_3 . f = forte, measured at reference pitch (RP) + 30 cents, p = piano, measured at RP – 30 cents. RP is concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone. ff (fortissimo), pp (pianissimo), and mf / mp (mezzo-forte / mezzo-piano) are general indications of dynamics that are defined specifically in each of the cited references. The error bars represent one standard deviation.

The subglottal measurements reported in [Hodge-FS 2001] for male loud speech (at 75% of their maximum dynamic range) does not have associated pitch information, so Figure 3 uses the typical male pitch range from [Williams-J 2010]. Likewise, the intraoral pressure measurements for consonants from [Subtelny 1966], table 1 (as cited in [Baken 2000], table 8-5) use the suggested pitch ranges for males, females and children from [Williams-J 2010]. [Enflo 2009] provides measurements for the lower limits of phonation at which speech becomes possible. Note that only the lower two frequencies of the male and female lower phonation limits are plotted. See Tables 2 and 3 in the Appendix for all data values plotted on Figure 3.

Figure 4 introduces a change in the vertical scale of pressure by a factor of five to accommodate higher pressure for musical instruments reported in the literature. Pressure measurements are plotted for the bassoon and oboe from two sources.

Figure 5 plots reported measurements on four additional Western classical instruments: the clarinet, alto saxophone, Western concert flute, and the alto recorder. See Table 1 in the Appendix for numeric data values.

Mean intraoral pressure on ethnic duct flutes was 7.26 ± 3.93 mBar and spanned a range of 0.48–47.23 mBar. This

range includes what might be considered extreme playing techniques on these instruments, since they were played as high as the ninth register in keeping with the procedures for this study. The subset of measurements on these instruments limited to playing at the reference pitch in registers 1–3, what might be considered a normal range of play on these instruments, gives a mean intraoral pressure of 5.75 ± 3.29 mBar and spanned a range of 0.48–25.86 mBar.

Figure 6 plots the results across the pitch range of ethnic duct flutes. It also plots subglottal pressure measurements from the literature for singing. See Tables 2 and 4 in the Appendix for all data values plotted on Figure 6.

Figure 7 plots the profile for three classes of instruments from this study:

- Ethnic reed instruments had a mean intraoral pressure of 50.38 ± 11.45 mBar and a range of 28.96–82.74 mBar.
- Ethnic reedpipes had a mean intraoral pressure of 18.07 ± 4.26 mBar and a range of 7.93–35.85 mBar.
- Ethnic overtone whistles had a mean intraoral pressure of 11.01 ± 4.84 mBar and a range of 0.28–64.26 mBar.

See Tables 5, 6, and 7 in the Appendix for all data values plotted on Figure 7.

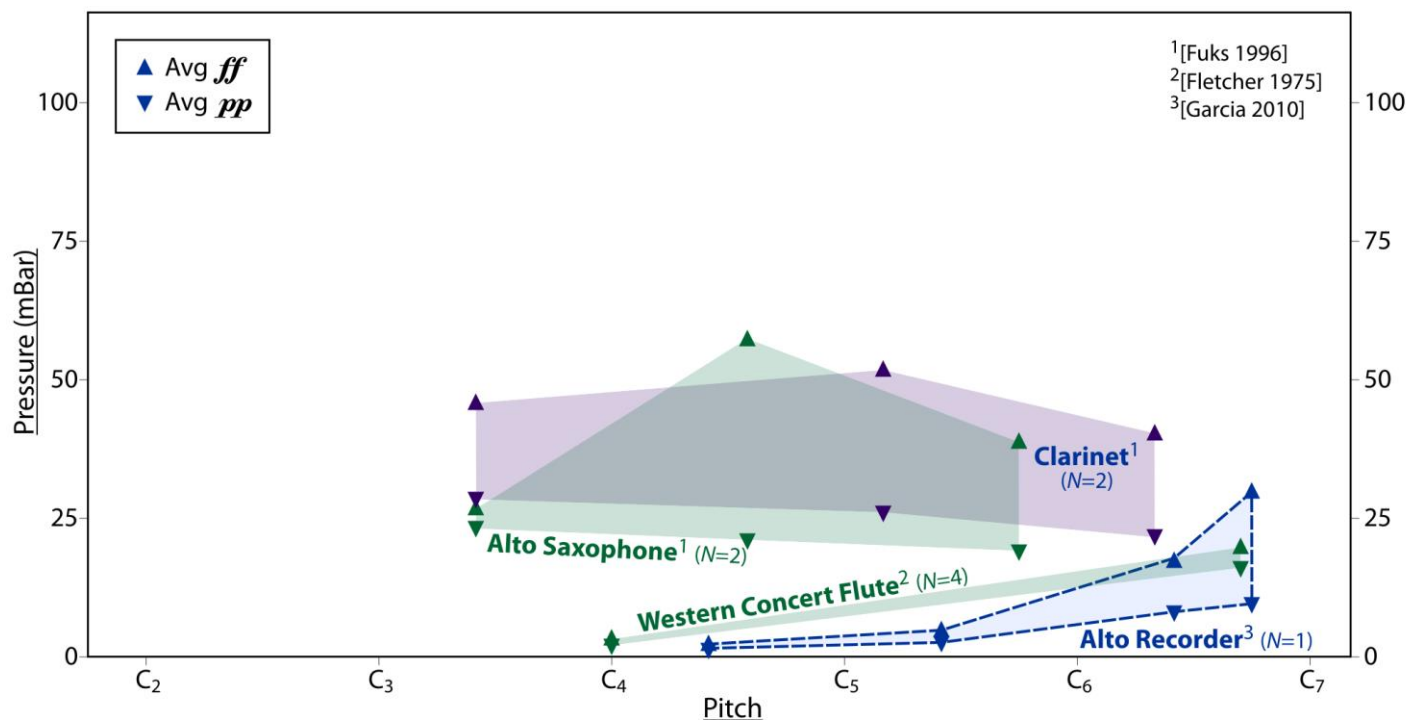


Figure 5. Woodwind instruments – intraoral pressure. *ff* (fortissimo), *pp* (pianissimo), and *mf* / *mp* (mezzo-forte / mezzo-piano) are general indications of dynamics that are defined specifically in each of the cited references.

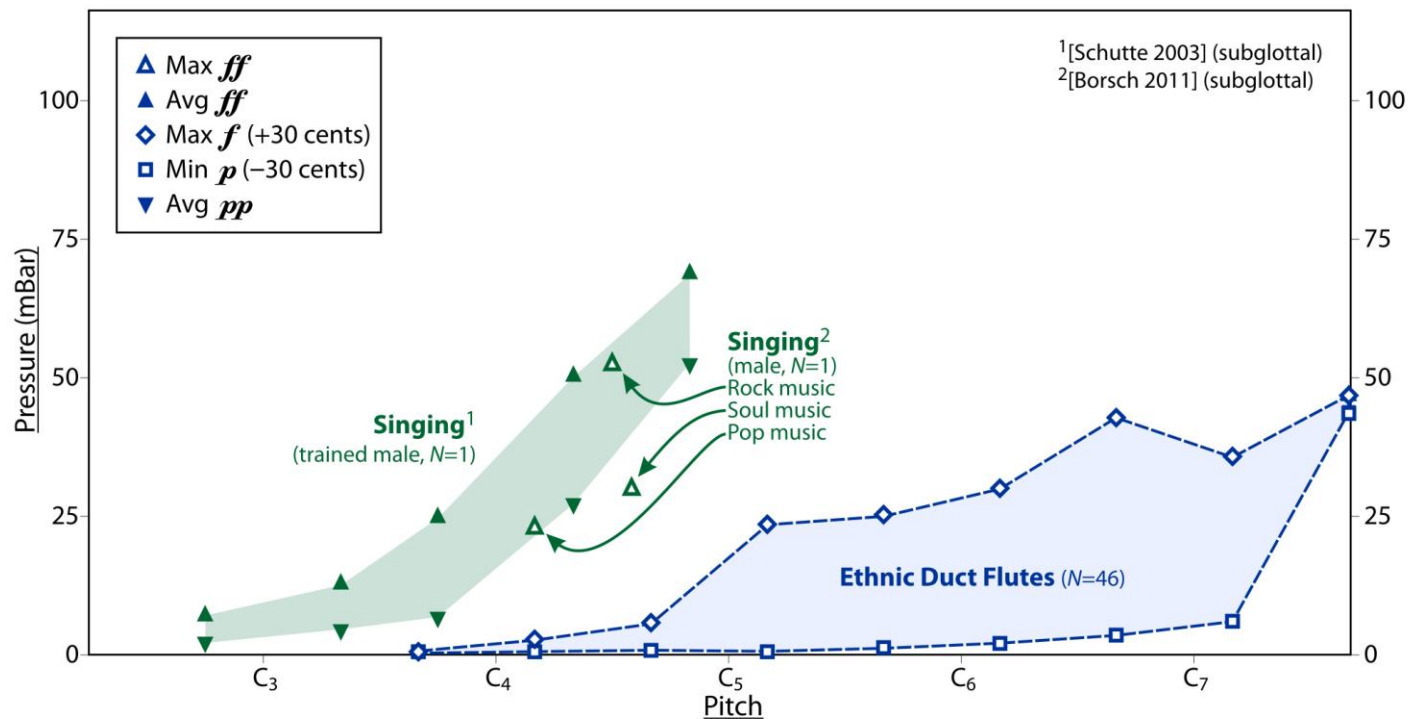


Figure 6. Ethnic duct flutes and singing – intraoral and subglottal pressure. Pitches for ethnic duct flutes are grouped into half-octave ranges. *f* = forte, measured at reference pitch (RP) + 30 cents. *p* = piano, measured at RP – 30 cents. RP is concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone. *ff* (fortissimo) and *pp* (pianissimo) are general indications of dynamics that are defined specifically in each of the cited references.

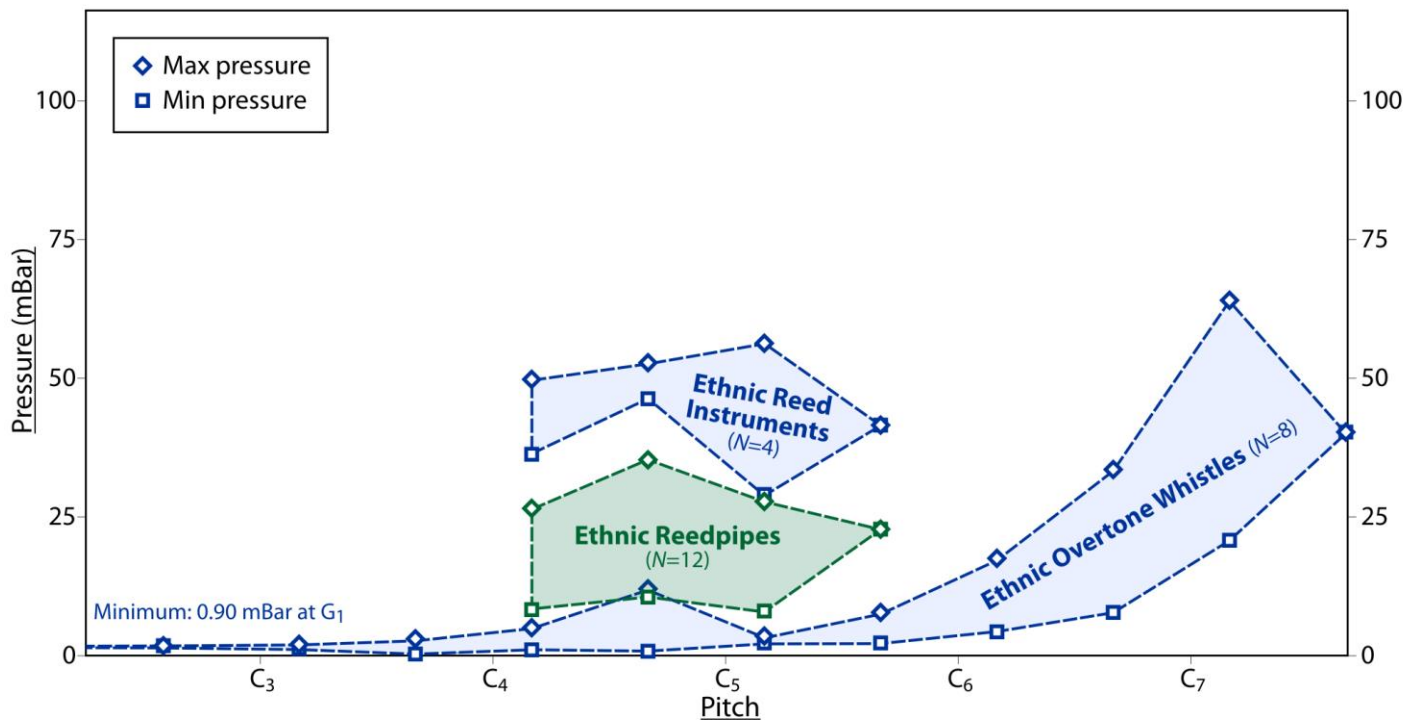


Figure 7. Ethnic wind instruments – intraoral pressure. Pitches are grouped into half-octave ranges, with each indicator showing the maximum or minimum intraoral pressure recorded across all measurements taken in that half-octave pitch range.

Mean intraoral pressure on ethnic overtone flutes was 6.94 ± 3.14 mBar and spanned a range of 0.55–30.68 mBar. Figure 8 plots the results across the pitch range of these flutes. It also plots intraoral pressure measurements for four brass instruments from the literature. See Table 8 in the Appendix for all data values plotted on Figure 8.

Breath Pressure Profile

In addition to the primary focus of this study, the measurements collected can shed light on some other issues of wind instrument design. One relates to the concept of a breath pressure profile (BPP) – the graph of intraoral pressure requirements on a single instrument or class of instruments as the player ascends the instruments scale.

Figure 9 charts the BPP for a subgroup of 67 Native American flutes.⁴ The lines connect data points for the root, fifth, and octave notes of the same dynamic.

This chart shows that, on the average, Native American flutes are constructed assuming a modest increase in breath pressure as the player moves up the scale, from 3.72 mBar at the root, to 4.74 mBar on the fifth, to 5.40 mBar on the octave note. It also demonstrates that the increase in breath pressure is, on average, linear through the three notes

measured and that the linear relationship holds across changes in dynamics.

Figure 9 also shows that a larger change in breath pressure is needed to raise pitch by 30 cents from concert pitch than to lower pitch by 30 cents. These results use the average readings across the three pitches at each of the dynamics: from the average intraoral pressure of 4.62 mBar for concert pitch, raising pitch by 30 cents required 3.42 mBar more pressure (+74.0%) and lowering pitch by 30 cents required 1.70 mBar less pressure (−36.9%).

Figure 10 shows another BPP plot of the primary notes for a single, well-tuned, six-hole, Native American flute. The lines on this plot are straight and pass through the pressure measurements for the root and the octave notes. The middle line for the *mf* readings at RP shows a slight increase in breath pressure as the player ascends the scale. Given that the upper and lower lines represent a deviation of 30 cents, it is apparent that the variations in tuning on each of the primary notes across the range of the instrument are no more than a few cents.

Discussion

Figure 2 highlights an interesting comparison between the intraoral pressure involved in speech and playing Native American flutes. This class of flutes grew from a tradition of poetic speech ([Nakai 1996], page 41), and Figure 2 lends

⁴ The four Native American flutes that could not maintain resonance at the *p* dynamic were excluded from this subgroup.

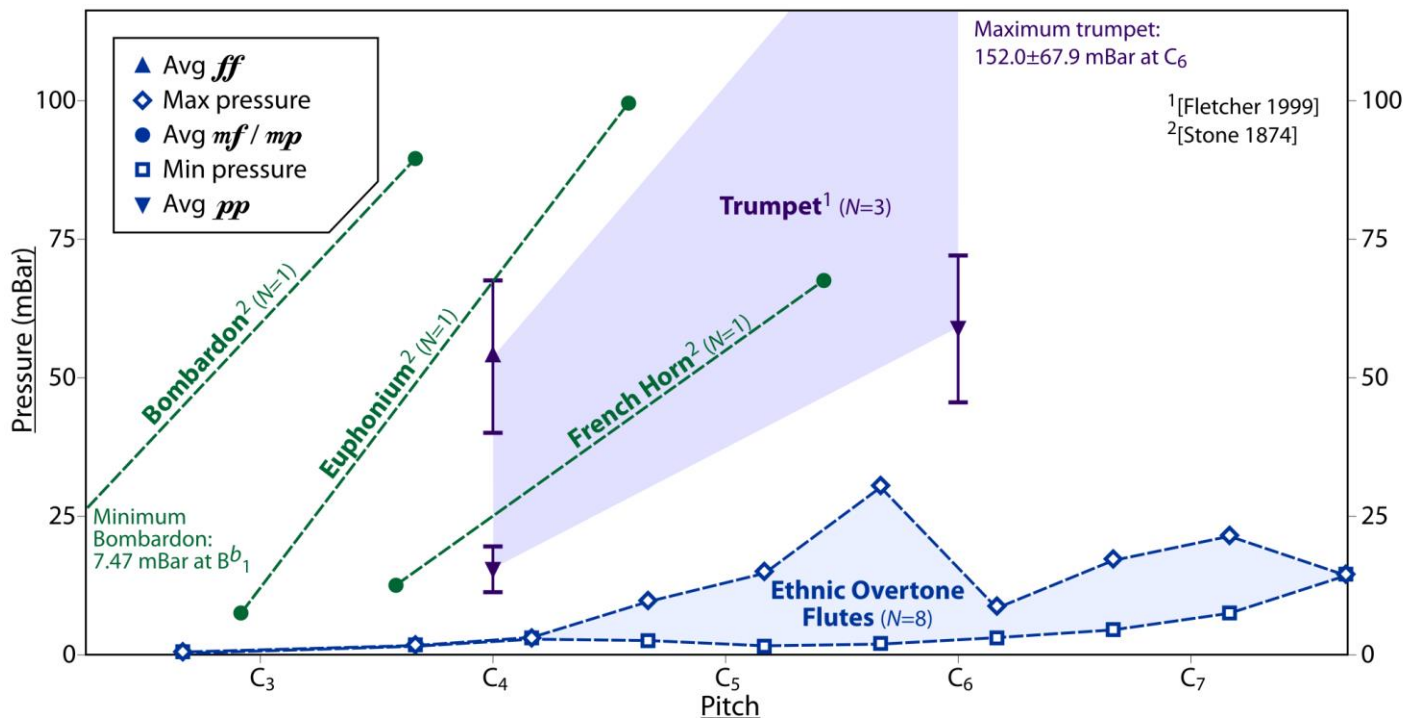


Figure 8. Brass instruments and ethnic overtone flutes – intraoral pressure. Pitches for ethnic overtone flutes are grouped into half-octave ranges, with each indicator showing the maximum or minimum intraoral pressure recorded across all measurements taken in that half-octave pitch range. *ff* (fortissimo), *mf*/*mp* (mezzo-forte / mezzo-piano), and *pp* (pianissimo) are general indications of dynamics that are defined specifically in each of the cited references.

empirical evidence to that historical link. Many aspects of speech do not involve intraoral pressure, since the mouth is often open. However, the limits of subglottal pressure and intraoral pressure involved in male loud speech, plosives and fricatives, and the lower phonation thresholds provide a striking correspondence to the limits of intraoral pressure for Native American flutes measured in this study.

A comparison between Figures 4, 5, and 7 shows that the intraoral pressure involved in playing ethnic reed instruments are roughly aligned with those of Western double-reed and single-reed instruments. Lower intraoral pressure was observed in ethnic reedpipes. It is interesting that the class of ethnic reedpipes includes instruments such as the Chinese bawu and hulusi that are generally widespread in use with amateur rather than professional musicians.

Play on ethnic duct flutes shows a rather large range on Figure 6. However, restricting play to a normal range on these instruments reduces the charted maximum intraoral pressure from 47.23 mBar to 25.86 mBar. This places ethnic duct flute roughly aligned with the one example of a Western duct flute, the alto recorder, charted in Figure 5.

The two classes of ethnic overtone instruments charted in Figures 7 and 8 show that, even though these instruments can perform in a wide range of registers and pitches, they

generally have low intraoral pressure requirements. The exception for these instruments is high pressure in ethnic overtone flutes in the extreme upper registers of these instruments. Given that these upper registers are used very briefly in typical play on these instruments, the transient use of these pressure spikes may allow players to avoid the health issues associated with high intraoral pressure.

Aside from the class of ethnic reed instruments that were part of this study, it appears that ethnic wind instruments, in general, have lower intraoral pressure requirements than most Western classical wind instruments.

The development of the concept of breath pressure profile in Figures 9 and 10 demonstrate that an intraoral pressure meter could be a significant aid to tuning wind instruments. The current practice among makers of these instruments is to use their own subjective personal preferences for breath pressure when tuning the instrument across the range of pitches. The use of an intraoral pressure meter would allow the maker to choose a desired breath pressure profile and objectively tune to that specific profile.

Limitations

Because the meter used in this study required a steady-state pressure of at least 333 msec, short-term intraoral

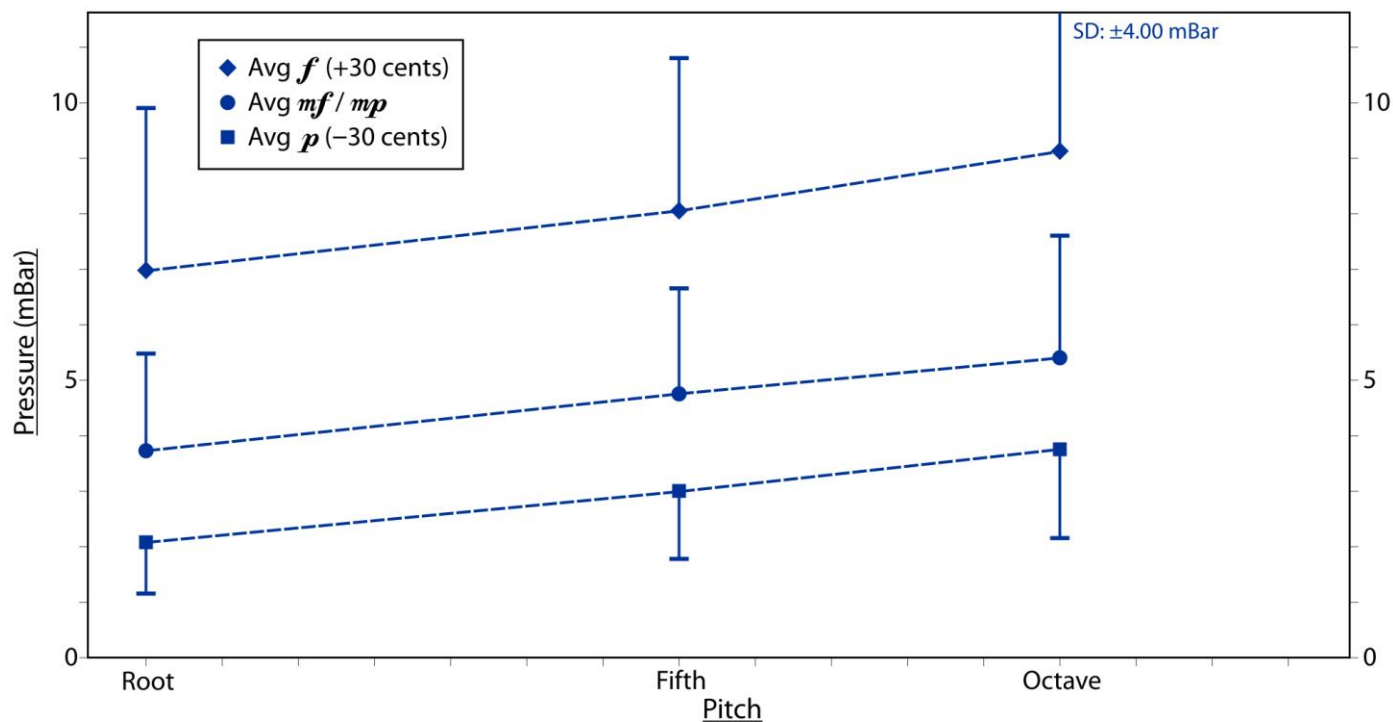


Figure 9. Breath pressure profile across the Native American flute range ($N=67$). f = forte, measured at reference pitch (RP) + 30 cents. mf/ mp = mezzo-forte / mezzo-piano, measured at RP. p = piano, measured at RP – 30 cents. RP is concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone.

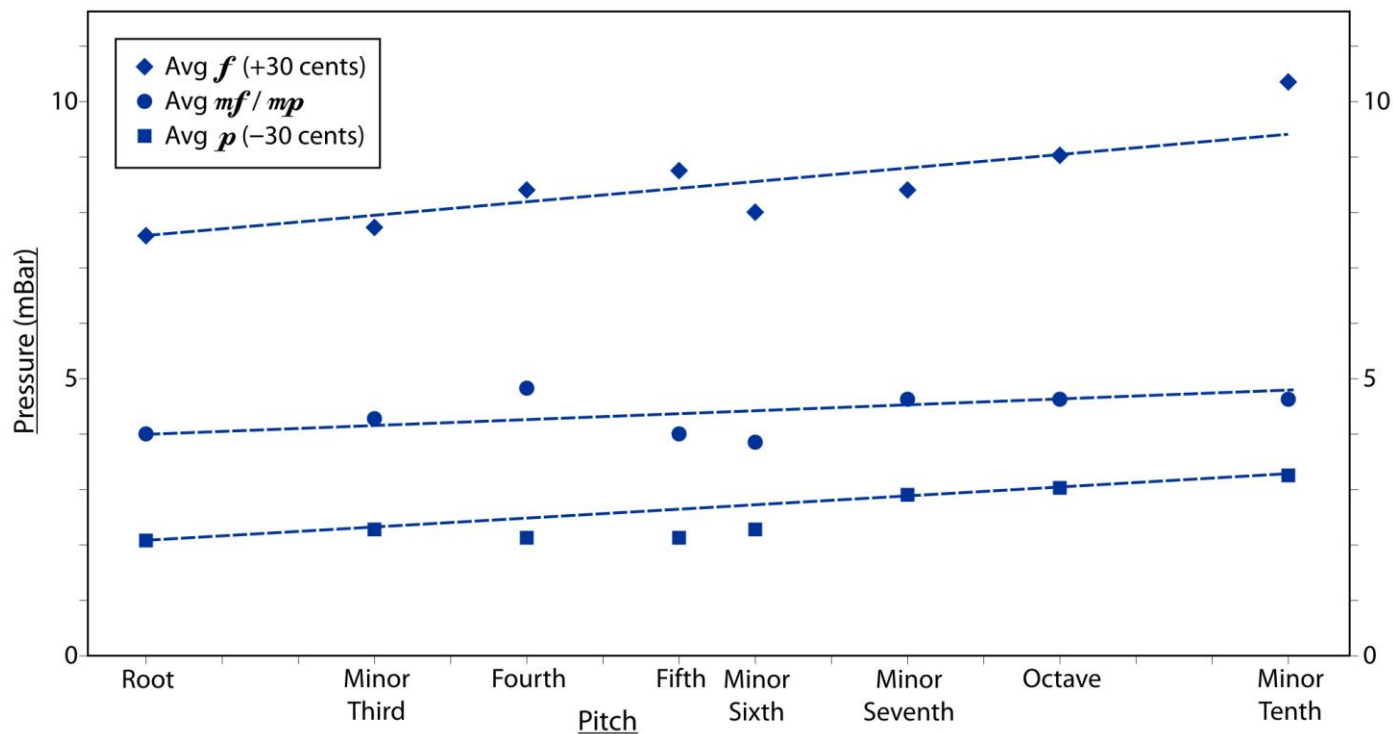


Figure 10. Breath pressure profile for a single Native American flute. f = forte, measured at reference pitch (RP) + 30 cents. mf/ mp = mezzo-forte / mezzo-piano, measured at RP. p = piano, measured at RP – 30 cents. RP is concert pitch based on A=440.

pressure changes could not be measured. This may be particularly important for instruments such as the Slovakian fujara, where short air bursts are used to very briefly sound in the extreme upper registers of the instrument

However, the goal of this study was to evaluate various ethnic instrument classes against the potential health implications identified for Western classical instruments. It appears likely, at least for some of those health issues such as intermittent high-pressure glaucoma, that long-held tones are the primary agent.

Other limitations include:

- The use of a single subject, the investigator.
- The widely varying conditions across the set of prior studies surveyed for the purpose of comparing instrument characteristics.
- The subjective evaluation of tone in establishing a reference pitch in the case of instruments that were not tuned to concert pitch.

Conclusions

This study was motivated by reports on a range of health issues associated with high intraoral pressure in some Western classical wind instruments and a lack of research in this area in ethnic wind instruments. Intraoral pressure was measured in six classes of ethnic wind instruments, and results were presented in the context of a survey of results across a broad range of wind instruments.

The results show that ethnic wind instruments, with the exception of ethnic reed instruments, have generally lower intraoral pressure requirements than Western classical wind instruments. The implication is that health issues that have been linked to high intraoral pressure in other studies are not an issue for these classes of ethnic instruments.

In the case of the Native American flute, the intraoral pressure requirements closely match the pressure involved in speech, a link that may be related to the instrument's roots in a tradition of poetic speech.

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For a general bibliography in the areas covered by this article, see http://www.Flutopedia.com/refs_bpress.htm.

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Appendix – Data Tables

The following pages provide numeric data for the charted data points that appear in the figures of this article.

Table 1. Musical Instrument Pressure Measurements Cited from the Literature

Instrument	Source	N	Concert		IOP (mBar)	Dyn	IOP (mBar)	Fig.
			Pitch	Dyn				
Alto Recorder	[Garcia 2010], Figure 5.13, graphic interpolation	1	F ₄	<i>ff</i>	3.60	<i>pp</i>	1.25	5
			F ₅	<i>ff</i>	5.20	<i>pp</i>	2.60	
			F ₆	<i>ff</i>	17.75	<i>pp</i>	8.00	
			A ₆	<i>ff</i>	30.10	<i>pp</i>	9.40	
Alto Saxophone	[Fuks 1996], Figures 16 and 18, graphic interpolation	2	F ₃	<i>ff</i>	27.17 ± 2.80	<i>pp</i>	22.91 ± 0.77	5
			G ₄	<i>ff</i>	57.65 ± 22.91	<i>pp</i>	20.95 ± 2.87	
			A ₅	<i>ff</i>	38.94 ± 4.62	<i>pp</i>	19.05 ± 3.36	
Bassoon	[Fuks 1996], Figures 28 and 30, graphic interpolation	2	C ₂	<i>ff</i>	23.58 ± 1.04	<i>pp</i>	12.52 ± 0.94	4
			B ₄	<i>ff</i>	69.17 ± 19.09	<i>pp</i>	28.69 ± 5.11	
Bombardon	[Stone-WH 1874]	1	B ₂	<i>mf</i>	7.47 ^a			8
			G ₄	<i>mf</i>	89.67 ^a			
Clarinet	[Fuks 1996], Figures 10 and 12, graphic interpolation	2	F ₃	<i>ff</i>	45.97 ± 2.35	<i>pp</i>	28.61 ± 2.86	5
			D ₅	<i>ff</i>	51.95 ± 2.91	<i>pp</i>	26.00 ± 1.58	
			E ₆	<i>ff</i>	40.35 ± 4.49	<i>pp</i>	21.60 ± 1.18	
Euphonium	[Stone-WH 1874]	1	B ₂	<i>mf</i>	12.45 ^a			8
			G ₄	<i>mf</i>	67.25 ^a			
French Horn	[Stone-WH 1874]	1	G ₃	<i>mf</i>	7.47 ^a			8
			G ₅	<i>mf</i>	99.64 ^a			
Oboe	[Fuks 1996], Figures 22 and 24, graphic interpolation	2	C ₄	<i>ff</i>	51.96 ± 4.59	<i>pp</i>	37.97 ± 2.72	4
			E ₆	<i>ff</i>	109.13 ± 14.82	<i>pp</i>	53.21 ± 0.21	
	[Adduci 2011], Table 14	4	D ₄	<i>mf</i>	41.32 ± 4.00			4
			G ₄	<i>mf</i>	43.80 ± 4.94			
			C ₅	<i>mf</i>	44.22 ± 4.52			
Trumpet	[Fletcher-NH 1999], Figures 1–3, logarithmic graphic interpolation	3	A ₅	<i>mf</i>	52.85 ± 3.26			8
			C ₂	<i>ff</i>	51.96 ± 4.59	<i>pp</i>	37.97 ± 2.72	
	[Fletcher-NH 1975], Figure 1, logarithmic graphic interpolation	4	B ₄	<i>ff</i>	109.13 ± 14.82	<i>pp</i>	53.21 ± 0.21	5
			C ₄	<i>ff</i>	51.96 ± 4.59	<i>pp</i>	37.97 ± 2.72	
	Western Concert Flute	[Coltman 1966] and [Coltman 1968], as charted in [Fletcher-NH 1975], Figure 1, logarithmic graphic interpolation	1	C ₄	<i>mf</i>	1.02		
C ₇				<i>mf</i>	9.16			
[Bouhuys 1965], as reported in [Fletcher-NH 1975], p. 233			C ₄		7.5–13			not charted
			A ₆		27–40			
		[Montgermont 2008], Figure 4d, graphic interpolation	1	D ₄	<i>ff</i>	1.60	<i>pp</i>	0.79
	D ₅			<i>ff</i>	4.76	<i>pp</i>	2.58	
	D ₆			<i>ff</i>	9.15	<i>pp</i>	6.63	

Note: Intraoral pressure measurements from various sources were converted to millibars, in many cases, by physically interpolating the location of data points. In some cases, the graphs use a logarithmic scale, which needed a non-linear interpolation. Dyn = Dynamic. IOP = Intraoral pressure. Fig. = the number of the figure in this article on which the data for the row is charted. ^aMeasurement given in whole inches H₂O.

Table 2. Vocal Pressure Measurements Cited from the Literature

	Source	N	Concert Pitch	Dyn	Pressure (mBar)	Dyn	Pressure (mBar)	Fig.
Singing	[Schutte 2003], Figure 3 – Average of 1974 and 1996 measurements, graphic interpolation	1	A ₂	<i>ff</i>	7.12 ^s	<i>pp</i>	2.45 ^s	6
			E ₃	<i>ff</i>	12.73 ^s	<i>pp</i>	4.79 ^s	
			A ₄	<i>ff</i>	24.87 ^s	<i>pp</i>	7.00 ^s	
			E ₄	<i>ff</i>	50.20 ^s	<i>pp</i>	27.46 ^s	
			B ^b ₄	<i>ff</i>	68.72 ^s	<i>pp</i>	52.82 ^s	
	[Borch 2011], Figure 7, graphic interpolation	1	F [#] ₄	Rock music	53.53 ^b			6
			G ₄	Soul music	29.92 ^b			
			D ₄	Pop music	24.37 ^b			
Speech	[Subtelny 1966], Table 1	10 males	G ₂ –G ₄ ^d	“natural and comfortable level”	6.64 ± 0.99 ^e			3
		10 females	A ₃ –G ₅ ^d		7.37 ± 2.13 ^e			
		10 children ^c	C ₄ –A ₅ ^d		10.28 ± 3.57 ^e			
	[Hodge-FS 2001], Figure 1c, graphic interpolation		G ₂ –G ₄ ^d	<i>ff</i> ^f	10.40 ± 2.80			3
	[Enflo 2009], Figure 5, graphic interpolation	9 males	F ₂	<i>ppp</i>	0.74 ^g			3
			F ₃	<i>ppp</i>	1.55 ^g			
		6 females	F ₃	<i>ppp</i>	0.72 ^g			
			A ₄	<i>ppp</i>	2.37 ^g			

Note: Pressure measurements are for intraoral pressure, unless indicated. Measurements were converted to millibars, in many cases, by physically interpolating the location of data points. Dyn = Dynamic. Fig. = the number of the figure in this article on which the data for the row is charted. ^sSubglottal pressure. ^bHighest subglottal pressure for the genre of music. ^cAge 6–10 years. ^dThe range of pitches for typical speech is from [Williams-J 2010]. ^eIntraoral pressure speaking the phoneme that causes the highest intraoral pressure across 15 consonants: «tʃ» (“ch”) in «itʃi» for males and children and «p» in «ipi» for females. ^f“75% of dynamic range”. ^gMeasurement of the quietest possible speech.

Table 3. Native American Flute – Intraoral Pressure

Concert Pitch	<i>n</i>	Pressure (mBar)			
		<i>f</i> -max	<i>f</i> -mean	<i>p</i> -mean	<i>p</i> -min
		RP + 30 cents		RP – 30 cents	
E ₃	3	5.93		1.65	
F [#] ₃ –B ₃	21	6.69	4.94	1.47	0.83
C ₄ –F ₄	54	9.51	5.86	1.63	1.03
F [#] ₄ –B ₄	144	14.13	6.63	2.28	0.90
C ₅ –F ₅	181	15.51	8.32	2.98	0.97
F [#] ₅ –B ₅	144	20.55	9.66	3.71	1.45
C ₆ –F ₆	48	17.03	8.92	4.04	2.00
F [#] ₆ –B ₆	10	11.79	9.93	5.26	3.93

Note: Intraoral pressure measurements across all Native American flutes ($N = 71$) are grouped by concert pitch into half-octave ranges. n = the number of measurements for that pitch range. RP = reference pitch, concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone.

Table 4. Ethnic Duct Flutes – Intraoral Pressure

Concert Pitch	<i>n</i>	Pressure (mBar)		
		<i>f</i> -max RP + 30 cents	<i>mf</i> -mean RP	<i>p</i> -min RP – 30 cents
F [#] ₃ –B ₃	1	0.48	0.48	0.48
C ₄ –F ₄	14	3.03	1.98 ± 0.65	0.55
F [#] ₄ –B ₄	34	6.00	2.64 ± 1.05	0.83
C ₅ –F ₅	73	23.86	3.86 ± 3.61	0.55
F [#] ₅ –B ₅	76	25.51	5.05 ± 3.38	1.31
C ₆ –F ₆	53	30.34	7.83 ± 4.46	1.93
F [#] ₆ –B ₆	36	43.02	13.54 ± 7.13	3.38
C ₇ –F ₇	19	36.27	18.16 ± 8.19	6.07
F [#] ₇ –B ₇	2	47.23	45.44 ± 1.79	43.64


Note: Intraoral pressure measurements across all ethnic duct flutes ($N = 46$) are grouped by concert pitch into half-octave ranges. n = the number of measurements for that pitch range. RP = reference pitch, concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone. Measurements were taken as with Native American flutes. Most of these flutes use the fingering  to produce the octave not in the second register. In addition, the fundamental note in each of the higher registers was attempted, as high as was possible on the instrument. These pressure measurements in the higher overtone registers were taken by establishing the pitch and then reducing breath pressure slightly to a point where the tone was stable — reference to precise tuning was not used in these higher overtone registers. The mean for each pitch range is taken over measurements at the reference pitch.

Table 5. Ethnic Reed Instruments – Intraoral Pressure

Concert Pitch	<i>n</i>	Pressure (mBar)		
		Maximum	Mean	Minimum
C ₄ –F ₄	2	49.99	43.09 ± 6.89	36.20
F [#] ₄ –B ₄	3	53.09	50.03 ± 2.87	46.19
C ₅ –F ₅	3	56.54	42.61 ± 11.26	28.96
F [#] ₅ –B ₅	1	41.51	41.51	41.51

Note: Intraoral pressure measurements across all ethnic reed instruments ($N = 4$) are grouped by concert pitch into half-octave ranges. n = the number of measurements for that pitch range. All measurements were taken on-pitch (*mf*).

Table 6. Ethnic Reedpipe Instruments – Intraoral Pressure

Concert Pitch	<i>n</i>	Pressure (mBar)		
		Maximum	Mean	Minimum
C ₄ –F ₄	12	26.75	18.66 ±5.45	8.14
F [#] ₄ –B ₄	12	35.85	17.14 ±4.13	10.48
C ₅ –F ₅	12	28.06	17.83 ±5.27	7.93
F [#] ₅ –B ₅	1	22.82	22.82	22.82

Note: Intraoral pressure measurements across all ethnic reedpipe instruments ($N = 12$) are grouped by concert pitch into half-octave ranges. n = the number of measurements for that pitch range. Most measurements were taken at the reference pitch (RP), and the reported mean is taken over those measurements. RP is concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone. On one instrument, it was possible to take measurements at $RP \pm 30$ cents and the maximum and minimum values reflect those additional measurements.

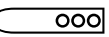
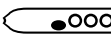
Table 7. Ethnic Overtone Whistles – Intraoral Pressure

Concert Pitch	<i>n</i>	Pressure (mBar)		
		Maximum	Mean	Minimum
G ₁	1	0.90	0.90	0.90
G ₂	1	1.65	1.65	1.65
D ₃	1	2.07	2.07	2.07
F [#] ₃ –B ₃	7	3.17	1.29 ± 1.00	0.28
C ₄ –F ₄	3	5.24	3.38 ± 1.79	0.97
F [#] ₄ –B ₄	9	12.13	4.01 ± 3.90	0.69
C ₅ –F ₅	6	3.72	3.03 ± 0.52	2.28
F [#] ₅ –B ₅	8	8.07	4.95 ± 1.69	2.14
C ₆ –F ₆	13	17.86	10.16 ± 3.97	4.21
F [#] ₆ –B ₆	13	33.78	19.98 ± 6.48	7.86
C ₇ –F ₇	5	64.26	36.87 ± 15.46	20.75
F [#] ₇ –B ₇	1	40.33	40.33	40.33

Note: Intraoral pressure measurements across all ethnic overtone whistles ($N = 8$) are grouped by concert pitch into half-octave ranges. n = the number of measurements for that pitch range. One pressure measurement was taken for each note in each register by establishing the pitch and then reducing breath pressure slightly to a point where the tone was stable — reference to precise tuning was not used for this class of instruments.

Table 8. Ethnic Overtone Flutes – Intraoral Pressure

Concert Pitch	<i>n</i>	Pressure (mBar)		
		Maximum	Mean	Minimum
F [#] ₂ –B ₂	2	0.69	0.62 ±0.07	0.55
F [#] ₃ –B ₃	2	1.65	1.55 ±0.10	1.45
C ₄ –F ₄	2	3.24	3.10 ±0.14	2.96
F [#] ₄ –B ₄	5	9.93	6.41 ±2.59	2.48
C ₅ –F ₅	8	15.31	7.89 ±5.30	1.52
F [#] ₅ –B ₅	11	30.68	14.84 ±11.43	2.07
C ₆ –F ₆	8	8.96	5.07 ±2.27	3.10
F [#] ₆ –B ₆	5	17.51	8.74 ±4.73	4.62
C ₇ –F ₇	4	21.79	13.77 ±5.47	7.38
F [#] ₇ –B ₇	1	14.75	14.75	14.75

Note: Intraoral pressure measurements across all ethnic overtone flutes ($N = 8$) are grouped by concert pitch into half-octave ranges. n = the number of measurements for that pitch range. Measurements were taken at reference pitch (RP) in the lowest note. RP is concert pitch based on A=440 or, for instruments not tuned to concert pitch, a breath pressure that subjectively produced a good tone. Measurements for the fifth note were taken using the fingering  or  in the first register, regardless of what pitch was produced. The fundamental note in each of the higher registers was attempted, as high as was possible on the instrument. These pressure measurements in the higher overtone registers were taken by establishing the pitch and then reducing breath pressure slightly to a point where the tone was stable — reference to precise tuning was not used in these higher overtone registers.

Dynamic Metrics of Heart Rate Variability



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Dynamic Metrics of Heart Rate Variability

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ARTICLE INFORMATION

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ABSTRACT

Numerous metrics of heart rate variability (HRV) have been described, analyzed, and compared in the literature. However, they rarely cover the actual metrics used in a class of HRV data acquisition devices – those designed primarily to produce real-time metrics. This paper characterizes a class of metrics that we term *dynamic metrics*. We also report the results of a pilot study which compares one such dynamic metric, based on photoplethysmographic data using a moving sampling window set to the length of an estimated breath cycle (EBC), with established HRV metrics. The results show high correlation coefficients between the dynamic EBC metrics and the established static SDNN metric (standard deviation of Normal-to-Normal) based on electrocardiography. These results demonstrate the usefulness of data acquisition devices designed for real-time metrics.

Introduction

Metrics of heart rate variability (HRV) are widely used in medical diagnostics, physiological research, and biofeedback training (TaskForce, 1996; Wheat & Larkin, 2010). HRV metrics are typically based on non-invasive measurements of cardiac function using electrocardiography (ECG) or photoplethysmography (PPG). A specific point is identified in each cardiac cycle, and the inter-beat interval (IBI) between those points in adjacent ECG heartbeats or PPG pulsebeats is measured.

Time intervals derived from ECG provide the input to a function that produces the HRV metric. Functions defined over PPG time intervals are often termed metrics of pulse rate variability (PRV).

A broad range of linear and non-linear HRV and PRV metrics have been developed based on statistical, spectral, geometric, neural network, and vector analysis techniques.¹ These metrics offer various tradeoffs in their computational complexity, applicability to real-time analysis, tolerance for physiological artifact and measurement artifact, and

significance with respect to particular medical or physiological conditions.

Most of HRV and PRV metrics described in published literature operate directly on a set of IBIs taken over a given length of time – we use the term *static metrics* in this article for these metrics. However, a wide selection of devices are available that provide metrics constructed in fundamentally different ways. These devices are typically designed for real-time reporting of metrics. Hence, we use the term *dynamic metrics* for the class of metrics provided by real-time data acquisition devices.

This article characterizes dynamic metrics and reports the results of a pilot study which compares one such dynamic metric with established HRV metrics.

ECG and PPG Metrics

In this article, we differentiate ECG-based metrics from PPG-based metrics using *e* and *p* postscripts, respectively. For example: SDNN_e and SDNN_p are variants of the widely-used SDNN metric of HRV. SDNN_e is the standard deviation of the intervals between adjacent R peaks of the QRS complex derived from normalized ECG measurements recorded over a given time period. SDNN_p is the

¹ An informal survey of published literature conducted by the second author has cataloged 69 distinct metrics, without distinguishing between ECG and PPG variants.

corresponding metric based on peaks in normalized PPG measurements.

Because of the relative ease of collecting PPG measurements in many situations, PRV metrics are often preferred to ECG-based HRV metrics. A number of studies have examined the relationship between the ECG and PPG variants of specific metrics, in particular SDNN (Johnston & Mendelson, 2005; Selvaraj, Jaryal, Santhosh, Deepak, & Anand, 2008; Teng & Zhang, 2003).

Dynamic Metrics

Dynamic metrics introduce a number of characteristics not typically found in static metrics:

Span. This extends the definition of IBI beyond the limitation of using adjacent cardiac cycles. The metric may be based on an IBI where the interval is a *span* measured between a given number, C , of cardiac cycles apart (span = C cycles) or between the cardiac cycles that are at least a given number, S , of seconds apart (span = S seconds).

An example is a metric defined over a heart rate (HR) derived from an IBI that spans 10 cardiac cycles.

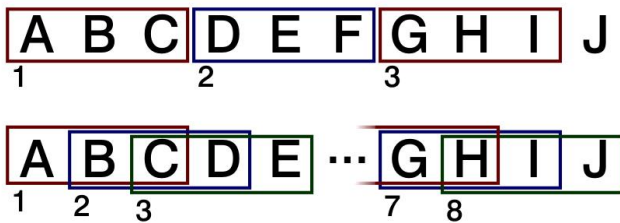


Figure 1. Two examples of sampling window progressions using sampling windows of size $W = 3$. A through J are inter-beat interval measurements. The upper example (Figure 1a) depicts sequential sampling windows and the lower example (Figure 1b) depicts moving sampling windows.

Sampling window. In the interest of producing real-time metrics, dynamic metrics are often calculated over a *sampling window* of IBI measurements. The size of the sampling window, typically denoted W , can be defined over time or cardiac cycles.

Static metrics use a sampling window that is typically the size of an overall study period and produce a single metric result. In dynamic metrics where the size of the sampling window is less than the study period, a sequence of metrics can be produced.

Progression. Sampling windows of measurement can be taken by moving the sampling window forward by the size of the window (*sequential sampling windows*, Figure 1a), by a single time interval or cardiac cycle (*moving sampling windows*, Figure 1b), or any other amount. In general, we use

the term *progression* for the rule which defines how the sampling window is moved.

Note in Figure 1 that **J**, the last data point, is not included in the sequential sampling windows but is included in the final moving sampling window.

Also note in Figure 1b that the initial and final $W-1$ data points of the study period participate in fewer moving windows than the more centrally-located data points. We call this characteristic of moving windows *center-bias*.

Aggregation. With the introduction of sampling windows, dynamic metrics can produce a sequence of results within a given study period. Those results can then be *aggregated* into a single metric for the study period. A common aggregation function (also called a *second-order function* or a *functional* in other contexts) is to take the mean of the results from each sampling window. However, other functions such as taking the standard deviation of the sampling window results might be useful in some contexts.

Estimated Breath Cycle

This study compared a dynamic metric, called estimated breath cycle (EBC), with some established metrics of HRV. EBC uses a sampling window whose size is based on an estimation of the length of a breath cycle of the subjects.

This study uses EBC metrics based on PRV (EBC_p) with sequential sampling windows of 10 seconds (EBC_p^{10s}) and 16 seconds (EBC_p^{16s}) and moving sampling windows of 10 seconds (EBC_p^{10m}) and 16 seconds (EBC_p^{16m}). Mean and SD functions are used to aggregate EBC metrics within a study period.

Method

Simultaneous measurements were taken using two independent systems on a single subject that included five periods of varying breathing rates.

EBC metrics were derived from a MindDrive™ finger sensor (Discovogue Infotonics, Modena, Italy). PPG levels were sampled at 24 Hz and processed data for HR were recorded at one-second intervals. HR readings on this system are derived from a weighted average of PRV intervals that span the 10 most recent pulsebeats.

PRV metrics other than EBC were derived from a Lightstone™ system by Wild Divine, Inc. (Las Vegas, Nevada). The Lightstone system reports instantaneous pulse rate by interpolating peaks between PPG readings taken at 30 Hz (Matt Cullen, Wild Divine, Inc., personal communication, June 28, 2012).

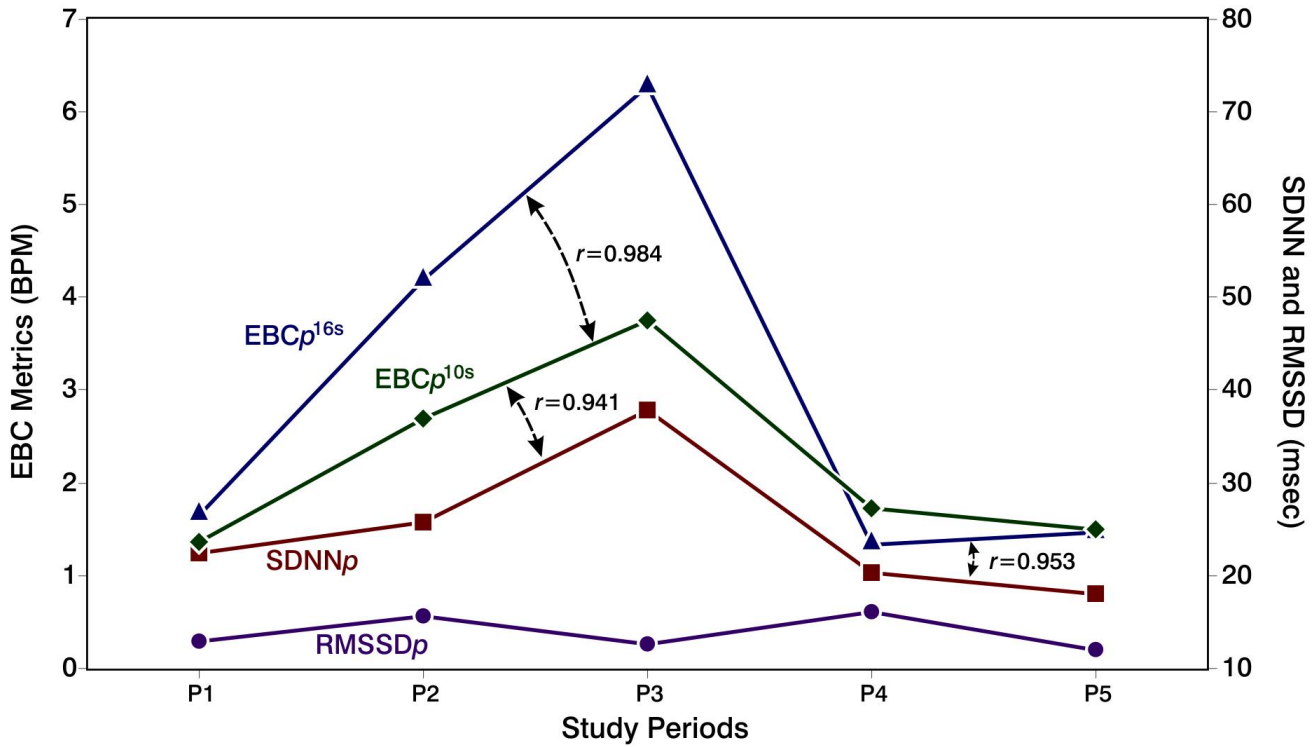


Figure 2. Comparison of estimated breath cycle (EBC) metrics of heart rate variability (HRV) with static HRV metrics. 10s and 16s indicate sequential windows of 10 and 16 seconds, respectively. SDNNp is the standard deviation of the intervals between adjacent peaks over the study period. RMSSDp is the square root of the mean of the sum of the squares of the intervals between adjacent peaks over the study period. All metrics are derived from normalized photoplethysmographic data.

Analysis

Artifacts were identified by visual inspection in both the MindDrive and Lightstone data streams. Time segments containing artifacts in either data stream were eliminated from the analysis.

Instantaneous pulse rate metrics from the Lightstone system were converted to IBIs, which formed the basis of all PRV metrics other than EBC.

Results

Figure 2 plots two of the EBC metrics against two static metrics, demonstrating a strong correlation between SDNNp and EBCp^{10s} ($r = .941$) and between SDNNp and EBCp^{16s} ($r = .953$). Numerical correlation coefficients are provided in Table 1 for all pairs of metrics.

Discussion

EBC – SDNN Correlation

The results of this pilot study demonstrated a very strong correlation between SDNNp and all the EBCp metrics.

The correlation between SDNNp and SDNNe (derived from ECG data) has been studied in three references:

Table 1. Pearson Correlation Coefficients between Metrics of Heart Rate Variability

Metric	Estimated Breath Cycle			
	Sequential windows		Moving windows	
	EBCp ^{10s}	EBCp ^{16s}	EBCp ^{10m}	EBCp ^{16m}
SDNNp	.941	.953	.960	.925
RMSSDp	.016	-.084	-.027	.042
SDSDp	.010	-.001	-.014	.106
EBCp ^{10s}	1	.984	.997	.990
EBCp ^{16s}	.984	1	.993	.991
EBCp ^{10m}	.997	.993	1	.992
EBCp ^{16m}	.990	.991	.992	1

- $r = .993$ based on the average of the three conditions reported by [Gil et al. \(2010\)](#), Table 2;
- $r = .989$ reported by [Medeiros \(2010\)](#), Table 6.3; and
- $r = .99$ specifically for PRV/SDNN from a PPG finger sensor reported in [Shi \(2009\)](#), Table 5-4.

Since Pearson's correlation coefficients are not transitive, it is not sound practice to combine them ([Castro Sotos, Vanhoof, Van Den Noortgate, & Onghena, 2008](#)), unless a pair of coefficients, r_a and r_b , satisfy the condition $r_a^2 + r_b^2 > 1$ ([Langford, Schwertman, & Owens, 2001](#)).

Combining the lowest SDNN_p – EBC_p correlation of $r = .925$ with lowest reported correlation of $r = .989$ for SDNN_p – SDNN_e, we get a value for $r_a^2 + r_b^2$ of 1.83. Based on this, we propose that the four EBC_p metrics studied correlate very strongly with SDNN_e.

EBC Correlation with RMSSD and SDDSD

Correlations with two additional static metric were performed:

- RMSSD_p is the square root of the mean of the sum of the squares of the successive differences between adjacent peaks of the PPG data over the study period.
- SDDSD_p is the standard deviation of the successive differences between adjacent peaks of the PPG data over the study period.

Both of these metrics are estimates of the short-term / high-frequency components of HRV (Thong, Li, McNames, Aboy, & Goldstein, 2003).

Two factors of the EBC metrics of this study were expected to “smooth” the data and mask high-frequency variations: the span of 10 cardiac cycles inherent in the HR data produced by the MindDrive and the sampling window itself.

As expected, the correlation between all EBC metrics and RMSSD and between all EBC metrics and SDDSD is quite low, ranging from $-.084$ to $+.106$.

Limitations

This pilot study measured a small sampling of the possible dynamic HRV metrics, using a single subject, and five study periods of unequal length. We would suggest a full study in this area be carried out to further validate correlations found in this pilot study.

Conclusions

This study tested the hypothesis that data acquisition devices based on PPG data and designed primarily for real-time HRV metrics could be useful in research studies. After characterizing the properties of the *dynamic metrics* gathered by those devices, a pilot study was carried out to compare those dynamic metrics with the metrics of HRV that are widely cited in the literature.

The results show high correlation coefficients between the EBC_p metrics and the established SDNN_e. These results demonstrate the usefulness of data acquisition devices designed for real-time metrics.

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