DYNAMIC MEASUREMENT OF INTRAORAL PRESSURE AND SOUND PRESSURE WITH LARYNGOSCOPIC CHARACTERIZATION DURING OBOE PERFORMANCE

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Dissertation Prepared for the Degree of

DOCTOR OF MUSICAL ARTS

UNIVERSITY OF NORTH TEXAS

December 2011

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Adduci, Michael Douglas. Dynamic measurement of intraoral pressure and sound pressure with laryngoscopic characterization during oboe performance. Doctor of Musical Arts (Performance), December 2011, 96 pp., 18 tables, 37 illustrations, bibliography, 41 titles.

Measurements of intraoral pressure (IOP) and sound pressure level (SPL) were taken of four oboists as they performed two sets of musical exercises: (1) crescendo-decrescendo from *pp* to *ff* and back to *pp* on the pitches D4, G4, C5 and A5, and (2) straight and vibrato performances of the same four pitches at *mf*. Video images of the vocal tract were also made using flexible fiberoptic nasoendoscopy (FFN). IOP and SPL data were captured in real time by the WinDaq®/Lite software package, with the dB meter located 8-9 inches in directly front of the oboe bell.

The study yielded minimum and maximum values from 21.04 to 57.81 mm Hg and from 65.53 to 100.89 dB across all pitches examined. Discussion is included for the following topics: (1) the oboe's sound envelope, or functional range of IOP and SPL values at different pitch levels, including the nonlinearity in the relationship between IOP and SPL on the oboe, (2) the static activation and kinetic maintenance thresholds for reed vibration, (3) the effect of vibrato on IOP/SPL, (4) the utilization of the vocal tract during execution of dynamic changes and vibrato, and (5) the impact of player experience on control of physical variables.

ACKNOWLEDGEMENTS

I would like to recognize and thank the members of my committee: Dr. John Scott, Dr. Kris Chesky for sharing his expertise and passion for research, and Dr. Charles Veazey for many years of inspired teaching and mentorship. Additionally, I am indebted to Dr. Fang Ling Lu of the University of North Texas Department of Speech and Hearing Sciences for contributing her resources, knowledge and unfailing enthusiasm to this project.

I would also like to thank Dr. Gordon Haramaki of the San José State University School of Music and Dance for his wisdom, guidance and friendship throughout the writing process. Finally, I am grateful to my father, Douglas Adduci, for his invaluable and timely help with statistics and data analysis.

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CHAPTER 1

INTRODUCTION

Background and Significance

> The study of the anatomy and physiology of the vocal organs is not indispensable to the pupil, but might be most useful to the teacher. It will enable him, when a defect is to be amended, to detect the organ which is at fault, and to suggest the proper correction. For the pupil it is enough that, localising [*sic*] his sensations through his master's explanations, he should learn to distinguish the various parts of his instrument and the manner of using them.[1]

Writing in the preface to the first edition (1840) of his influential pedagogical work on singing techniques, Manuel Garcia was perhaps one of the earliest available examples of a musician and teacher applying the principles of scientific investigation to the practice of his art. He stated the value of empirical, practical knowledge about the human body in equipping teachers and performers to pursue excellence in their craft.

In the study of music, the transmission of knowledge from teacher to student emphasizes apprenticeship and oral tradition, whereby the student attempts to copy the master's techniques and methods through imitation. This method of learning, endorsed by Garcia, is effective provided the teacher is able to elucidate correct procedures to the student. However, even the most talented teachers and performers may not completely understand how what they do physically produces the aesthetic result they obtain, and so students can learn, for instance, to breathe or to articulate in a certain way simply because that is how their teachers believe (correctly or not) they perform that action themselves.

[1] Manuel Garcia, *Hints on Singing*, new rev. ed., trans. Beata Garcia (London: Ascherberg, Hopwood and Crew, Ltd., 1894), iii-iv.

This process can perpetuate misinformation, because sometimes a technically incorrect explanation is the most effective way to make a point about musicianship. The goal, in this case polished musicianship, is emphasized rather than the means, and the teacher tacitly accepts a misleading explanation as long as the outcome is desirable. For example, consider the topic of respiration as it relates to tone production. For many years wind instrumentalists have perpetuated the concept of diaphragmatic exhalation, while a study of anatomy reveals that in fact, the diaphragm functions as a muscle of inspiration and plays only a passive role in expiration.[2]

The breathing apparatus has been well covered elsewhere and does not need reexamination here.[3] Regardless of how it is truly utilized in respiration, the diaphragm does provide a convenient label for the teacher attempting to convince a student to control their breathing from the abdominal region. This is important for oboists, as breathing from high in the chest contributes to a tight, thin tone quality. The process of balancing the abdominal and intercostal muscles to generate a steady, focused air stream is therefore simplified to the easier concept of blowing from the diaphragm. It is likely that the performer does not clearly feel which muscles are actually involved, as King et al. and Rydell et al. observed when studying laryngeal function in musicians.[4] The desired aesthetic result may be achieved but the student may be exerting themselves unnecessarily by trying to contract muscles that cannot be used in that way.

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[2] The correct information has also been taught: Robert Sprenkle and David Ledet, *The Art of Oboe Playing* (Miami: Summy-Birchard Music, 1961), 13-14.

[3] E. J. M. Campbell, “The Respiratory Muscles,” *Annals of the New York Academy of Sciences* 155, Article 1 (1968): 135; Scott Nelson, *Breathing for Musicians* (Winchester, Virginia: Reinhardt & Still Publishers, 1999), 9-19.

[4] Austin I. King, Jon Ashby, and Charles Nelson, “Laryngeal Function in Wind Instrumentalists: The Woodwinds,” *Journal of Voice* 1, no. 4 (1988): 366; Roland Rydell et al., “Laryngeal Activity During Wind Instrument Playing: Video Endoscopic Documentation,” *Logopedics, Phoniatrics, Vocology* 21 (1996): 43.

Consider a second example of this phenomenon. Smith et al. demonstrated that, compared to the general population, musicians are better able to estimate and reproduce set levels of inspiratory pressure.[5] Payne also determined that for expiratory pressure, humans can distinguish between different levels of pressure within the magnitude required for speech, but their accuracy diminishes as the target level increases.[6] This is further shown in a study of air pressure in oboe performance by Anastasio and Bussard, who found that their subjects gave widely varying estimates of the air pressure required to play their instrument, ranging from 20 to 90 pounds per square inch (PSI). When the subjects then blew into a pressure gauge, the maximum pressure they could produce was between 2.5 and 3.5 PSI, while the maximum obtained from playing the oboe was less than 1 PSI.[7] In this case, the performers' expectations and perceptions had very little to do with the physical realities of their instrument. The authors stated,

> It is interesting to note that neither the musician nor the nonmusician would say he could inflate an automobile tire, although such is implied in a mouth air pressure of 20 psi [*sic*] or more.
>
> Given the basic role of mouth air pressure in playing wind instruments, it seems strange that so little systematic knowledge can be found, and that so much discrepancy exists between belief and substantiated evidence. . . .
>
> Thus a knowledge of air pressure requirements and the profile of an instrument is useful to the performer, teacher, acoustician, and instrument designer.[8]

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[5] J. Smith et al., "Sensation of Inspired Volumes and Pressures in Professional Wind Instrument Players," *Journal of Applied Physiology* 68, no. 6 (1990): 2382-83.

[6] Amy Jannelle Payne, "Intraoral Air Pressure Discrimination for an Open Versus Closed Tube Pressure System" (MA thesis, University of Florida, 1987), 22, 24-26, 29-30.

[7] Angelo Anastasio and Nicholas Bussard, "Mouth Air Pressure and Intensity Profiles of the Oboe," *Journal of Research in Music Education* 19 (1971): 62, 69.

[8] Ibid., 62, 68.

This, then, is the crux of the case for applying the principles of empirical research to the study of music. It is important that musicians, particularly those that plan to teach other musicians, understand the physiology behind their art, so that they can more effectively and correctly communicate that art to their students and enable them to reach their maximum potential. With that aim in mind, this project was designed to study the use of air pressure and the resultant yield of sound pressure in oboe playing.

Statement of Purpose

The purpose of this study was to characterize the intraoral pressures generated during performance of tones on the oboe under varying conditions of pitch and loudness. The specific aims of the study were to measure intraoral pressure and sound pressure for pitches (1) performed on a continuum of dynamic levels from very soft to very loud, and (2) performed at a constant dynamic level both with straight tone and with vibrato.

CHAPTER 2

STATE OF RESEARCH

Terms and Definitions[1]

Pressure and force are not the same; a force is an influence that causes a change in the shape, speed or direction of an object. Force has both direction and magnitude, and it acts on something: “The hydraulic press applied 10 pounds of force to the aluminum can.” Pressure is a description of how a force acts on a given area, and is measured relative to the size of the affected area. Therefore, intraoral pressure (IOP) is the pressure applied to the surfaces of the oral cavity by the air stream during its use in respiration, speech, singing, or in playing a wind instrument. Similarly, the sound pressure level (SPL) of a sound does not describe its loudness; it is an expression of the sound’s pressure (force acting on the eardrum) relative to the minimum threshold of human hearing, and is reported in decibels (dB).[2]

There are many units available to represent air pressure. The most commonly used units in the literature pertaining to musical instruments are the millimeter of mercury (mm Hg), representing the amount of pressure needed to displace the mercury in a manometer by 1 mm (1 pound per square inch = 51.715 mm Hg), and the centimeter of water (cm H_2O), describing a similar relationship with water (1 cm H_2O = 0.736 mm Hg). In this document I report all air pressure measurements in mm Hg.

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[1] Unless otherwise indicated, definitions in this section were adapted from J. D. Cutnell and K. W. Johnson, *Physics*, 5th ed. (New York: John Wiley and Sons, Inc., 2001), chap. 11 and 14.

[2] “Sound and Noise: Characteristics of Sound and the Decibel Scale” [website], available at: http://www.epd.gov.hk/epd/noise_education/web/ENG_EPD_HTML/m1/intro_5.html, accessed 12 June 2011.

Measurement of intraoral pressure does not give a complete picture of the effort exerted by the performer, for two reasons. First, air pressure is not the same at all points in the air column. Some studies, particularly those focused on speech or singing, have measured subglottal pressure (SGP) instead – this is the air pressure present in the trachea below the glottis. Measuring SGP is an invasive process; two methods, still in use today, require the subject either to swallow a pressure transducer to place it in the esophagus below the vocal folds so that pressure changes in the trachea can translate to the esophagus for measurement, or to insert a needle transducer into the subglottal trachea by penetrating the exterior of the neck.[3] Bouhuys also refers to a direct catheterization of the subglottal region by anesthetizing the glottis and inserting a catheter down the trachea.[4]

Due to this difficulty in measurement, researchers will often use IOP as an estimate of SGP. There is some evidence that while the pressure in these two locations is nearly equal under the low-pressure conditions of speech or singing, this is not the case under conditions of higher pressure as in the playing of a wind instrument, and so IOP cannot be used to estimate SGP for high pressure applications.[5] Even though air pressure can be measured at various locations throughout the respiratory tract, intraoral pressure remains a useful metric when studying wind instruments because IOP is the pressure level that directly influences vibration of the reed and subsequent tone

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[3] M. H. Draper, Peter Ladefoged, and D. Whitteridge, "Respiratory Muscles in Speech," *Journal of Speech and Hearing Research* 2, no. 1 (1959): 16-17.

[4] Arend Bouhuys, Donald F. Proctor, and Jere Mead, "Kinetic Aspects of Singing," *Journal of Applied Physiology* 21, no. 2 (1966): 483.

[5] Kazutomo Kitajima and Fumika Fujita, "Estimation of Subglottal Pressure with Intraoral Pressure," *Acta Otolaryngologica* 109, nos. 5-6 (1990): 477.

production, regardless of pressure variations elsewhere in the air column and whether or not IOP may be regulated by another element of the expiratory apparatus.

The second point of concern is that the researcher collecting pressure measurements is not directly measuring the performer's muscular activity. Rather, air pressure is generated as a result of the performer's physical effort during exhalation. Because of this distinction, one should avoid assuming a direct linear relationship between muscular contraction and resultant air pressure. Air pressure data provide a useful reference for discussion of performance requirements, but a doubling of air pressure does not necessarily indicate a doubling of muscular contraction.

Survey of Relevant Literature

In the 1950s and 1960s, studies began to appear that directly examined air pressure as used in wind instrument performance. In 1966 Bouhuys reported measurements collected across the entire range of the oboe. When playing *pp* oboists averaged IOP values between approximately 24-28 mm Hg and sound pressure levels between 69-75 dB across low, middle and high pitches, and when playing *ff* the values increased to approximately 28-38 mm Hg and 87-90 dB. He contrasted these measurements with data from the French horn, which yielded approximately 5-22 mm Hg and 61-82 dB for *pp* pitches, and approximately 10-75 mm Hg and 83-100 dB for *ff* pitches.[6] From these results it is clear that the oboe has a more limited range than the French horn, both in terms of blowing pressure and dynamic level, and also that the oboe requires a higher average blowing pressure than the French horn in most cases, except for the very highest pitches when played at the loudest dynamic.

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[6] Arend Bouhuys, "Lung Volumes and Breathing Patterns in Wind-Instrument Players," *Journal of Applied Physiology* 19 (1964): 971.

In 1969 Black and Hyatt studied the maximum inspiratory and expiratory pressures of men and women aged 20-54 using a measurement device that produced static loading of the air column via a small (2 mm) aperture for air to escape from the end of the device. This provided an adequate simulation of playing a small-aperture wind instrument such as the trumpet or oboe. They measured mean values for maximum inspiratory pressure of 91.3 mm Hg for men and 64.0 mm Hg for women, and maximum expiratory pressure of 171.5 mm Hg for men and 111.9 mm Hg for women.[7]

These maximum values for exhalation seem relatively high compared to Bouhuys' measurements for the oboe and French horn playing at *ff*. It is possible that when playing loudly the musician is not blowing as hard as they can, to avoid producing a poor tone quality, and the instrument itself may limit the maximum blowing pressure. However, Bouhuys also reported a maximum of 158 mm Hg from a trombonist playing with a mute,[8] and a much later study by Fletcher and Tarnopolsky measured a maximum IOP of 187.52 mm Hg for a trumpeter playing as loud as possible.[9] Even the air pressure measurements for the softest dynamics performed on musical instruments are substantially greater than those required for speech: Payne reported a maximum of approximately 6.6 mm Hg for the highest-pressure consonant phonemes (/n/ and /p/).[10]

Later work in the 1970s and 1980s focused on quantifying the human maximum for air pressure generation independent of any instrument. These studies frequently

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[7] Leo F. Black and Robert E. Hyatt, "Maximal Respiratory Pressures: Normal Values and Relationship to Age and Sex," *American Review of Respiratory Disease* 99 (1969): 696, 700.

[8] Bouhuys, "Lung Volumes," 972.

[9] Neville H. Fletcher and A. Tarnopolsky, "Blowing Pressure, Power, and Spectrum in Trumpet Playing," *Journal of the Acoustical Society of America* 105, no. 2, pt. 1 (1999): 875.

[10] Amy Jannelle Payne, "Intraoral Air Pressure Discrimination for an Open Versus Closed Tube Pressure System" (MA thesis, University of Florida, 1987), 3.

produced conflicting conclusions. Schorr-Lesnick et al. published a large study in 1985 determining that wind instrumentalists could not generate greater inspiratory and expiratory pressures than a control group; their results were in direct conflict with Bouhuys' earlier research.[11] In addition, Fiz et al. produced conflicting data of their own in 1993 by showing that trumpet players could in fact produce greater inspiratory and expiratory pressures than nonmusicians.[12]

The oboe is considered a high pressure instrument by musicians and nonmusicians alike, and it is frequently used by composers to play extended musical lines with limited breathing opportunities. Despite this reputation, and the fact that oboists occasionally complain about a sensation of back-pressure when playing, the recent literature indicates that oboe performers actually generate less than half the maximum intraoral pressure of trumpet performers: Fuks and Sundberg recorded values from 51-88.5 mm Hg for two oboists playing *ff* near the top of their high range in one study, and between 26.5-71.4 mm Hg for the pitches C4, E5 and D6 on the oboe in a second, earlier study.[13] These values are substantially lower than the previously-mentioned maximum of 187.52 mm Hg for the trumpet.

Writing in 1970, Weber and Chase stated that the oboe is distinct from other wind instruments in its continuous maintenance of at least 25 mm Hg of IOP over long periods of time, and that IOP is higher in oboe playing because air flow is relatively

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[11] Beth Schorr-Lesnick et al., "Pulmonary Function in Singers and Wind-Instrument Players," *Chest* 88, no. 2 (1985): 203-4; Bouhuys, "Lung Volumes," 978.

[12] José A. Fiz et al., "Maximum Respiratory Pressures in Trumpet Players," *Chest* 104, no. 4 (1993): 1204.

[13] Leonardo Fuks and Johan Sundberg, "Blowing Pressures in Bassoon, Clarinet, Oboe and Saxophone," *Acta Acustica united with Acustica* 85, no. 2 (1999): 275; Leonardo Fuks, "Aerodynamic Input Parameters and Sounding Properties in Naturally Blown Reed Woodwinds," *Speech, Music and Hearing: Quarterly Progress and Status Report* 4 (1998): 4.

low.[14] In 2004 Schwab and Schultze-Florey elaborated on these points, suggesting that while brass instruments are capable of much higher maximum pressures, the oboe requires a higher average pressure than the trumpet in order to produce a steady tone. Studying 19 oboists and 15 trumpeters, they measured a minimum pressure of 28 mm Hg, a normal range from 30-48 mm Hg, and a maximum value of 94 mm Hg for the oboe, and a minimum of 7 mm Hg, a normal range of 13-42 mm Hg, and a maximum of 131 mm Hg for the trumpet.[15]

These data show that the minimum, average and maximum values for intraoral pressure on oboe are very similar, while the minimum and average values for trumpet are much lower but its maximum is very high. Therefore, the oboist, while not really playing with tremendous air pressure, is constantly sustaining what would be considered an above average pressure on other instruments. For the body this is an abnormal condition, as the intraoral pressures required for speech are both transitory and much lower than the pressures required for instrumental performance; thus the performer perceives a sensation of high pressure.[16]

Oboists' perception of discomfort and back-pressure increases during a long musical passage; the increase in intraocular pressure (pressure in the eye) and blood pressure in the head that comes from long-term constriction of the thoracic cavity is a possible contributor. Venous return of blood to the heart relies primarily on gravity and physical movement, so when the oboist is blowing steadily the blood in the head is less

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[14] Jaroy Weber, Jr. and Robert A. Chase, "Stress Velopharyngeal Incompetence in an Oboe Player," *Cleft Palate Journal* 7 (1970): 861.

[15] Burkard Schwab and Andreas Schultze-Florey, "Velopharyngeal Insufficiency in Woodwind and Brass Players," *Medical Problems of Performing Artists* 19, no. 1 (March 2004): 23.

[16] Arend Bouhuys, "Pressure-Flow Events During Wind Instrument Playing," *Annals of the New York Academy of Sciences* 155, Article 1 (1968): 268.

able to return through the neck. Meanwhile, the arterial flow into the head is not impeded, causing an increase in blood pressure in the head that could be related to the oboist's sense of back-pressure and distress during long phrases.[17]

Most research related to intraoral pressure measures a series of individual notes in isolation; for example, in 1964 Bouhuys studied the lowest and highest note for each instrument, and every concert A pitch in between.[18] Fuks and Sundberg were one of the first teams to address the importance of musical context in studying intraoral pressure, by measuring IOP throughout the performance of complete arpeggios and orchestral excerpts.[19] They found that how or why a note is approached, and how or why it is left, influenced the IOP used by performers to produce that note: the bassoonists in their 1999 study used less IOP to play a certain note during an arpeggio than they used to play the same note in an isolated context.[20]

One possible explanation for the variation in pressure values reported from the 1960s to the present is that the technology for obtaining this data has changed dramatically during this period. Bouhuys measured IOP using a small latex balloon inserted into the subject's mouth and connected to a pressure transducer to measure its compression during the performance.[21] In contrast to this very invasive method, an

[17] Joel S. Schuman et al., "Increased Intraocular Pressure and Visual Field Defects in High Resistance Wind Instrument Players," *Ophthalmology* 107 (2000): 129-30; Pinar Aydin et al., "Effect of Wind Instrument Playing on Intraocular Pressure," *Journal of Glaucoma* 9 (2000): 323-24.

[18] Bouhuys, "Lung Volumes," 969.

[19] Leonardo Fuks and Johan Sundberg, "Respiratory Inductive Plethysmography Measurements on Professional Reed Woodwind Instrument Players," *Speech, Music and Hearing: Quarterly Progress and Status Report (TMH-QPSR)* 1-2 (1998): 40-42.

[20] Fuks and Sundberg, "Blowing Pressures in Bassoon, Clarinet, Oboe and Saxophone," (1999): 272.

[21] Arend Bouhuys, "Sound-Power Production in Wind Instruments," *Journal of the Acoustical Society of America* 37, no. 3 (1965): 453.

improved apparatus appeared around 1970 that used a small catheter tube (1-2 mm in diameter) connected to a pressure transducer to collect the same data in a less intrusive way. The catheter was placed in various locations in the mouth, usually affixed to the teeth to hold the tube in place. In this situation the tube and mounting device still represent a departure from normal performance conditions, especially if the tube is mounted close to the uvula.[22] By 1971 Anastasio and Bussard had already further reduced this apparatus to an unmounted catheter held by the performer in the corner of their mouth; their results for oboe players were between 10.3-36.2 mm Hg.[23]

The equipment and method used to record and process data has also evolved over time. Prior to the advent of computer software suites for data collection, measurements were either recorded by hand from analog pressure gauges[24] or by printing out graphical data in real time on a sheet of grid paper, similar to the output of a polygraph.[25] The former method does not facilitate monitoring of a pitch throughout its entire lifespan, as the researcher has to choose a moment (or moments) in time to read the gauge, while the latter lacks resolution, as the real-time data track is a graph that does not provide specific, detailed numerical values for any given moment – they must be inferred from the graph.

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[22] For examples of this technology, see (1) A. J. Walpole Day and T. D. Foster, "The Measurement of Variations in Intraoral Air Pressure," *The Angle Orthodontist* 40, no. 1 (1970): 45-46; (2) E. Kent Fritch and John H. Saxman, "Dental Appliance for Support of Intraoral Air Pressure Sensors," *Journal of Dental Research* 50, no. 4 (1971): 980.

[23] Angelo Anastasio and Nicholas Bussard, "Mouth Air Pressure and Intensity Profiles of the Oboe," *Journal of Research in Music Education* 19 (1971): 64, 69.

[24] See Black and Hyatt, "Maximal Respiratory Pressures," 697 for a picture of this type of apparatus. Static analog pressure gauges were still in use as late as 1999: Fletcher and Tarnopolsky, "Blowing Pressure," 874.

[25] See Day and Foster, "Measurement of Variations," 46 for a diagram of this type of data readout.

Real-time data capture became the new standard of experimental assessment in the 1990s, along with the increased availability and manageable size of personal computers and the development of software useful for statistical analysis. As early as 1998 Fuks began publishing studies that collected data by connecting digital sensors directly to a computer for processing.[26] This allows for detailed analysis as the data are tightly packed and are available both in graphical and numerical format.

A final issue related to variation in air pressure measurements among different studies is that the oboe is a highly variable instrument worldwide, both in its construction and in the technique used to play it and to make its reeds, and there has been a tremendous amount of development and change in how oboists play between the 1950s and the present. Today there remain substantial differences between national styles of performance and reed making, and even among American oboists there is wide variation in approach to pedagogy, reed making and performance technique. Considering these factors, it may be impossible to draw general conclusions about IOP requirements for the oboe without accounting for differences in technique and equipment.

The studies described in this chapter, among others, have laid the experimental and methodological groundwork for future research into the physical parameters used in oboe performance, providing the opportunity to continue to expand our knowledge of how this delicate and mysterious instrument functions using the recently developed ability to track and gather data in real time both graphically and numerically.

[26] Leonardo Fuks, "Assessment of Blowing Pressure Perception in Reed Wind Instrument Players," *Speech, Music and Hearing: Quarterly Progress and Status Report* 3 (1998): 37.

CHAPTER 3

EXPERIMENTAL METHOD

Characterization of Subject Population

The subjects for this project were four oboists drawn from the population of graduate and undergraduate oboe majors at the University of North Texas. None of the subjects reported use of tobacco, and all reported only infrequent alcohol use, if any; no major medical conditions pertinent to the respiratory tract were reported. All subjects made and used their own reeds. Table 1 summarizes the relevant demographic data.

Table 1. Subject Demographics

Subject ID	Gender (M/F)	Age	Years of Experience	Instrument Model	Brand of Cane	Brand of Staple
1	M	29	18	Lorée	Davies	Pisoni
2	M	27	9	Buffet Greenline	Ghys	Chudnow-E
3	F	24	11	Lorée	Alliaud	Sierra
4	F	21	11	Lorée	Ghys	Pisoni

These four subjects provided a total of six experimental sessions, as Subject 3 performed the complete experiment twice on different days, and Subject 4 performed several of the exercises twice during the same session but with the laryngoscope in a lower position. Their initial performances are designated 3A and 4A, with the second performances labeled 3B and 4B. Before conducting the experiment the project was approved by the Institutional Review Board at the University of North Texas; the project description and informed consent form approved by the IRB and presented to all test subjects is included in the Appendix.

Description of Musical Tasks

Each subject performed a pair of musical tasks, labeled A and B. A metronome was used throughout each session to help standardize the length of each subject's performance; both tasks were performed at 88 beats per minute. To aid in written discussion of these experiments, I refer to the pitch "middle C" on the grand staff as C4, the third-space C in treble clef as C5, and the C above the treble clef staff as C6. Other pitches are labeled based on the octave of the closest C below their pitch. Both tasks in this study used the pitches D4, G4, C5, and A5. Figure 1 shows the music performed for Task A: a standard long-tone exercise with a slow crescendo followed by a slow diminuendo. Task A uses a minimum dynamic marking of *pp* and a maximum marking of *ff*; each subject was instructed to interpret these dynamic marks as they felt appropriate.

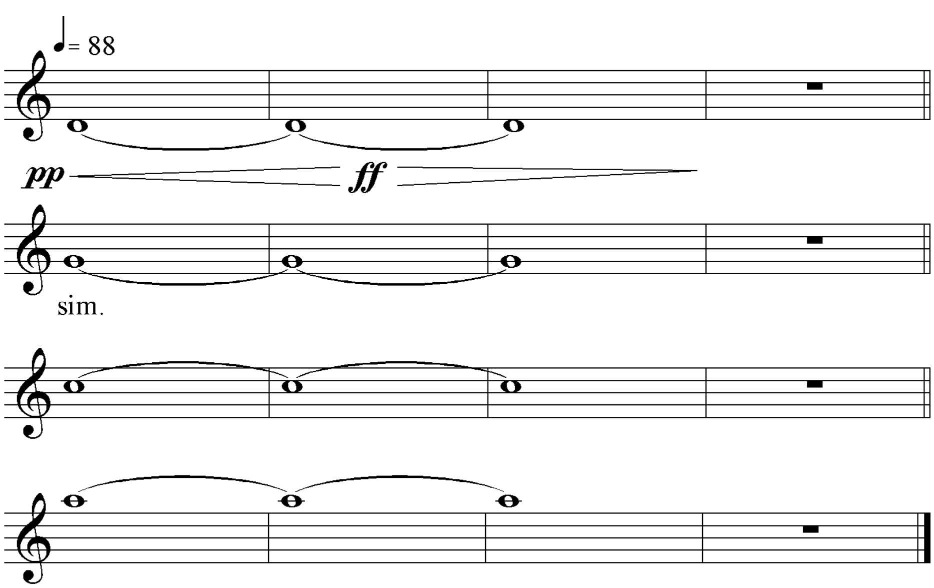

Figure 1. Musical Task A – Dynamic Contrast

Task B was a study of vibrato, and is shown in figure 2. For this task, the subjects played each pitch at a constant, medium dynamic level, first with a straight tone and then again with vibrato. The subjects were instructed to interpret the *mf* dynamic marking in their own way, rather than trying to meet a target volume level.

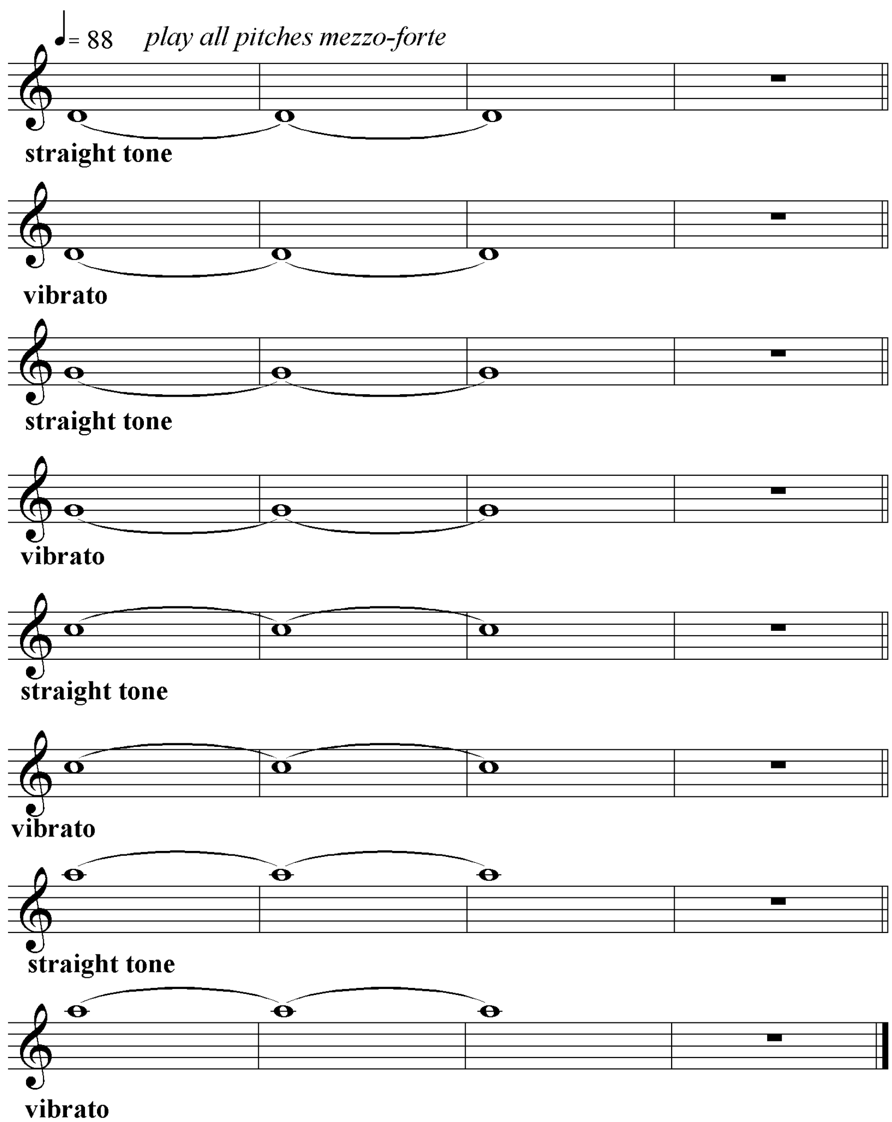

Figure 2. Musical Task B – Vibrato

Equipment and Experimental Setup

The experiment was performed in the speech pathology laboratory at the University of North Texas Speech and Hearing Center, a small room (approximately 12' x 8') with smooth, cement walls, a tile floor and a standard industrial/commercial lay-in panel ceiling. The subjects were seated in the middle of the room in front of a music stand; the stand's center shaft was 19 inches away from the front of the chair.

The experiment involved three types of data acquisition: measurement of intraoral pressure (IOP), measurement of sound pressure (SPL), and capture of video footage of the pharynx and larynx. Sound pressure was measured with a standard analog decibel (dB) meter attached to the bottom of the music stand's desk, resulting in a distance of between 8-9 inches from the oboe bell to the dB meter. Intraoral pressure data was collected using a pressure-to-voltage transducer built by George Kondraske, professor of electrical and biomedical engineering at the University of Texas at Arlington. Figures 3 and 4 show the assembled transducer.

Figure 3. Pressure Transducer

The transducer was attached to the bell of the subject's oboe using hook-and-loop fastener straps. A plastic catheter, 2 mm in external diameter, was run along the body of the oboe from the transducer up to the reed and secured to the oboe using twist ties (avoiding interference with the oboe's keys). The tube was then attached to the thread portion of the oboe reed using a twist tie and was arranged to lie to the right and approximately 1 mm behind the distal edge of the reed.[1] With the oboe in playing position, the opening of the tube was inside the subject's mouth without interfering with the formation or seal of the embouchure around the reed, and without being occluded by the tongue during articulation. When the subject blew into the reed, the tube conducted the air pressure in the subject's oral cavity to the pressure transducer for measurement. All subjects tolerated this device without difficulty.

Figure 4. Catheter Ready for Attachment to the Oboe Reed

[1] In this usage, *distal* refers to the tip, being the portion of the reed furthest away from the oboe. Additionally, in this context the word *tip* does not refer to the entire tip region of the reed, but to the very distal end of that region – the point on the reed that is furthest away from the oboe, where the act of articulation takes place.

The pressure-voltage transducer, decibel meter and a standard battery-powered metronome were connected to a DATAQ® Instruments model DI-720 data acquisition system, which was then connected to a laptop computer running the WinDaq®/Lite software suite to collect the IOP and SPL data along with a metronome mark for time standardization. The instrumentation and software package recorded 80 data points per second for intraoral pressure (measured in volts)[2] and sound pressure (measured in dB). This real-time data monitoring allowed a close examination of the complete profile (initiation, propagation and termination) of each note performed. The raw numerical data gathered by WinDaq®/Lite was exported to Microsoft® Excel® 2003 and IBM® SPSS® Statistics 17.0 for analysis.

Finally, video footage of the vocal tract was gathered using a transnasal fiberoptic laryngoscope. This endoscopic procedure, called flexible fiberoptic nasoendoscopy (FFN), was performed by Fang Ling Lu, professor of speech-language pathology at the University of North Texas. The video record of each session was divided into quadrants: the endoscopic camera view, the real-time WinDaq® data graph for reference purposes, and two external camera views to document the experiment. An audio recording of the session was also made, synchronized with the video and computer data to aid in identifying different portions of the session during analysis.

The laryngoscope was not equipped with a measurement scale and so no quantitative visual data are available from the scope for use in relating air or sound pressures to glottal or throat aperture. Additionally, depending on each subject's

[2] To present the data in a meaningful format, the voltage readings from the pressure transducer were converted to mm Hg. For the pressure transducer used in this study, 1 volt is equal to 101.4 mm Hg. The formula used for conversion was $p = (v-a)*101.4$, where ***v*** is a voltage event recorded by the pressure transducer, ***a*** is the ambient pressure in volts measured during that task, and ***p*** is the resultant intraoral pressure for that event, converted from volts to mm Hg.

individual tolerance for the endoscopic procedure, the camera was not in the same vertical position in the vocal tract for each subject, so measuring the video footage directly is not possible due to the different level of vertical zoom for each subject's imagery based on camera placement. Therefore I use still images from the endoscopic camera for reference and illustration only.

Experimental Procedure

After listening to the experimental protocol and privacy policy for the study, signing an informed consent form, and completing a demographic questionnaire, each subject was seated facing a music stand as described above. They received a spray of lidocaine in their nostrils and throat to ease any discomfort from the FFN procedure. Once this took effect, the laryngoscope was inserted in the subject's nose, passing through the nostril and nasal cavity and descending behind the soft palate into the oropharynx behind the uvula to provide visual imagery of the vocal folds and the base of the tongue during the performance of the musical exercises.[3] I refer to this camera placement as the superior (elevated) position. Subject 4 tolerated the laryngoscope well enough to allow a second performance of the musical tasks, with the laryngoscope in a deeper position adjacent to the base of the tongue and epiglottis to improve the camera's view of the vocal folds. I refer to this deep camera placement as the inferior position. With the laryngoscope in place each subject performed the musical exercises as described above. The entire experimental process took 10 minutes to complete the paperwork, 15 minutes to set up and insert the laryngoscope, and 15 minutes for each iteration of the musical exercises.

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[3] For an explanation of the anatomy of this region, see Albert L. Merati and Anthony A. Rieder, "Normal Endoscopic Anatomy of the Pharynx and Larynx," *American Journal of Medicine* 115, no. 3A (2003): 10S-14S.

Protocol for Data Analysis

The tables shown in chapter 4 summarize a set of descriptive statistics calculated for each subset of the experimental system. The statistics reported (and their abbreviations) are the sample size (*n*), referring to the number of data points collected during each subject's performance, the mean ($\bar{x}$), the standard deviation (SD), and the range (shown as the minimum and maximum recorded values). I use these symbols and abbreviations for all tables throughout this document. Subject 4B represents that subject's performance with the laryngoscope in the inferior position near the epiglottis; all other subjects had the laryngoscope in the superior position behind the uvula. Additionally, the final row of each table shows results for all subjects collected as an aggregate unit.

Figure 5 is a sample dual-axis line graph (IOP is always shown on the left axis in black, with SPL always shown on the right axis in grey) showing the initiation, propagation and termination phases of a single note from this study. The performance of a pitch begins with the performer's generation of an air column, measured as a buildup of air pressure inside the oral cavity. IOP must reach a certain level before the oboe reed will begin to vibrate; I call this value the *static activation threshold* of the reed.[4] The actual IOP required to meet the static activation threshold and start producing an audible tone varies depending on the performer's desired dynamic level at sound initiation, tessitura of the starting pitch, the acoustical properties of the starting

[4] The concept of an activation threshold is well-documented both in the field of acoustics, and in study of intraoral pressure in musical instruments; see (1) Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments*, 2d ed. (New York: Springer-Verlag, 1998), 481-83; (2) Leonardo Fuks and Johan Sundberg, "Blowing Pressures in Reed Woodwind Instruments," *Speech, Music and Hearing: Quarterly Progress and Status Report* 3 (1996): 47-50; (3) Neville H. Fletcher and A. Tarnopolsky, "Blowing Pressure, Power, and Spectrum in Trumpet Playing," *Journal of the Acoustical Society of America* 105, no. 2, pt. 1 (1999): 877.

pitch on that performer's individual instrument (different oboes show more or less resistance to starting a tone, depending on age, condition, brand, model, and variance in manufacture within a brand or model), and the vibratory kinetics of the particular reed under the particular environmental conditions at that moment (altitude, humidity, temperature and barometric pressure).

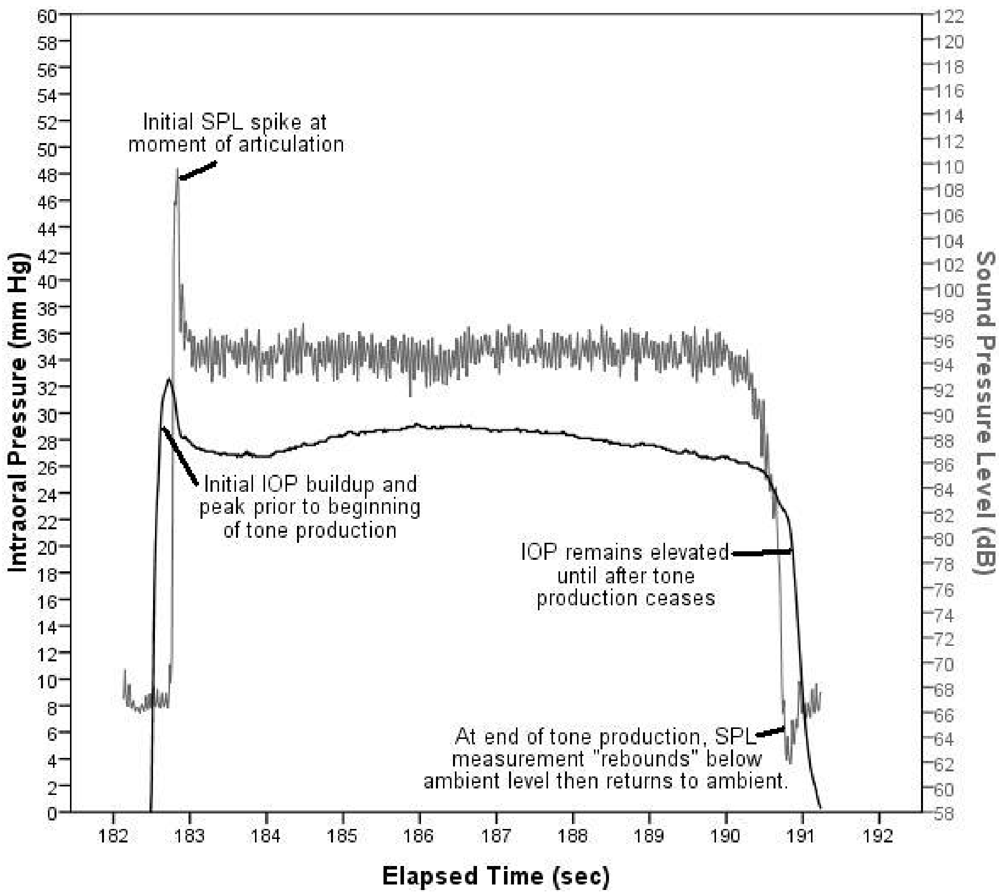


Figure 5. Sample Dual-Axis Line Graph

Through practice and training the oboist instinctively learns to time their attempt at sound production with the moment their air pressure reaches the required level, assessed based on how their reed feels to them and what they know about the characteristics of their instrument and embouchure. A common method for starting a tone following silence is to occlude the end of the reed with the tongue, blow against that closed aperture until air pressure reaches the correct threshold, and then remove the tongue from the reed allowing the tone to start. This type of initial articulation helps to reduce the accent caused by crossing the static activation threshold, but depending on the factors described above a certain amount of accent may be unavoidable. This is visible in figure 5 as a spike in both IOP and in SPL at the start of the tone. The SPL spike occurs at the moment audible tone is produced; the IOP spike occurs just before.

When the oboist is ready to end the tone, the process requires reducing SPL while maintaining IOP to prevent the note from going flat. Figure 5 illustrates this principle: the IOP curve returns to ambient levels only after the SPL curve has done so. In oboe pedagogy this process of sustaining IOP beyond the end of the audible tone is called *tapering* the release of the note – stopping the tone suddenly produces an undesirable lurch in the musical line that is only appropriate in the context of repeated staccato articulations where separation is desired. Finally, note that at the end of tone production, the SPL curve dips below the ambient level and then returns to it. This is due to the damped response of the dB meter's circuitry (the same electronic damping must also be a component of the initial dB spike, but its contribution would be difficult to determine without extensive calibration and testing). These parameters for beginning and ending a tone are typical of the results obtained during this study.

When reporting descriptive statistics on the data captured in this project, I chose to restrict the sample to only data points collected while audible tone was actually being produced. I excluded data points collected during the preparation and withdrawal of the air column. The initial spike in SPL caused by the act of articulation is an undesirable artifact of the oboe reed that oboists strive to minimize, and it also gives an artificially high SPL measurement not related to how soft the performer can actually play that pitch. For Task A, I set the beginning of tone production at the first data point immediately following the initial articulation spike in SPL.

It is difficult to separate the true end of a note from the performer's tapered release of that note, so I used a 10-point moving average (0.125 seconds) to smooth the SPL curve and then applied a derivative function (dv/dt, also using a 10-point moving average) to find the point of greatest change in SPL at the end of the note. I set this data point as the end of tone production. Figure 6 shows an example of this dv/dt function as a note is released.

For Task B the subjects were producing pitches without dynamic alteration, to the best of their ability. Therefore, when analyzing the data from Task B I used the same protocol described above for Task A, but in addition I moved the start point for each note forward to 0.5 seconds (40 data points) after the top of the initial dB spike, and I moved the end point backward 0.5 seconds before the SPL derivative's point of greatest negative slope. In this way, I was able to remove most if not all of the artifacts associated with starting and ending a pitch but retain as much useful data as possible from the propagation phase of the note. Note that the line graphs presented throughout this document always show the entire progress of their note including preparation and release; the truncation protocol described above was only used for data analysis.

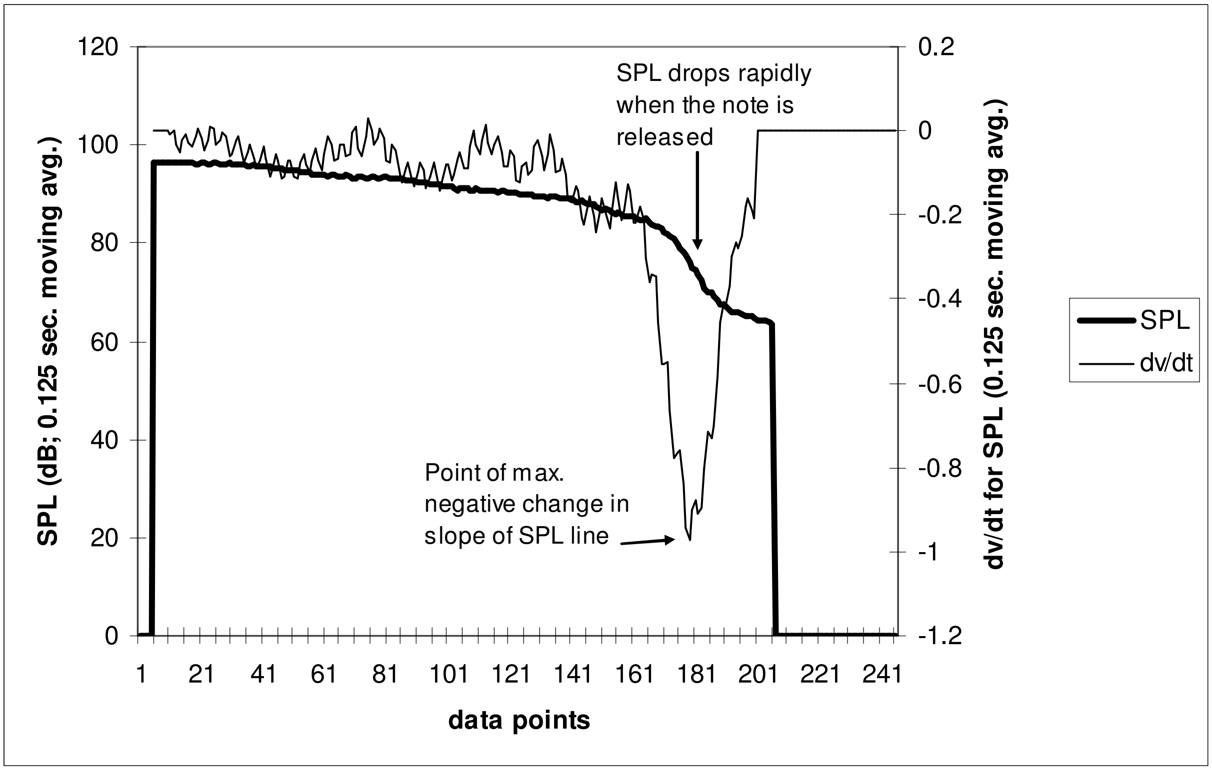


Figure 6. Derivative Function (dv/dt) for SPL

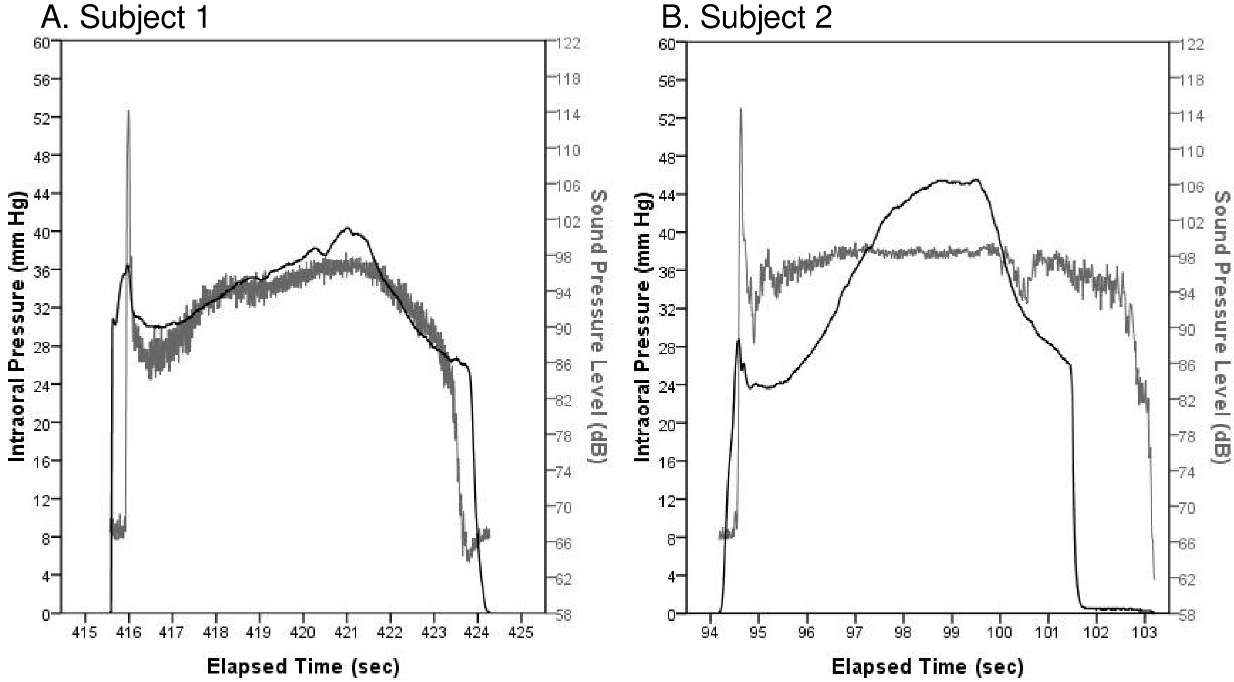
CHAPTER 4

RESULTS OF EXPERIMENT

Task A

The experimental subjects produced a total of six performances of Task A, five with the laryngoscope in a superior position and one with the laryngoscope in an inferior position (Subject 4B). Figure 7 shows line graphs of all individual performances of the pitch D4 from this task. Table 2 reports the sample size (*n*), mean ($\bar{x}$), and standard deviation (SD) for the intraoral pressure (IOP) and sound pressure (SPL) data collected during all D4 performances. Subject 2's performance (figure 7B) had an IOP sensor artifact beginning at 101.5 seconds, probably caused by the subject's tongue occluding the sensor tube. This prevented the IOP sensor from capturing data at the end of the performance; I omitted these data points when calculating descriptive statistics for D4.

A. Subject 1 B. Subject 2



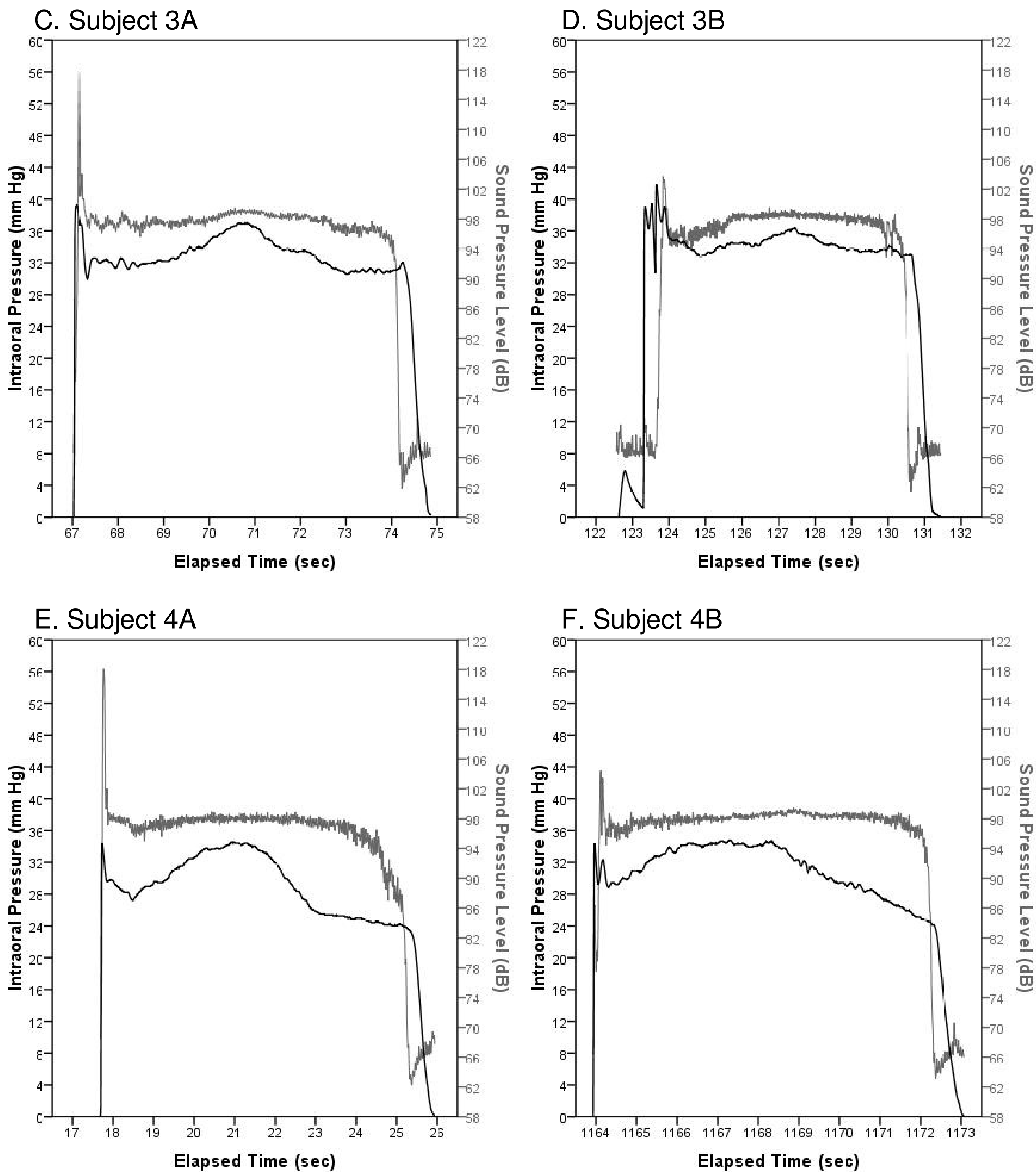


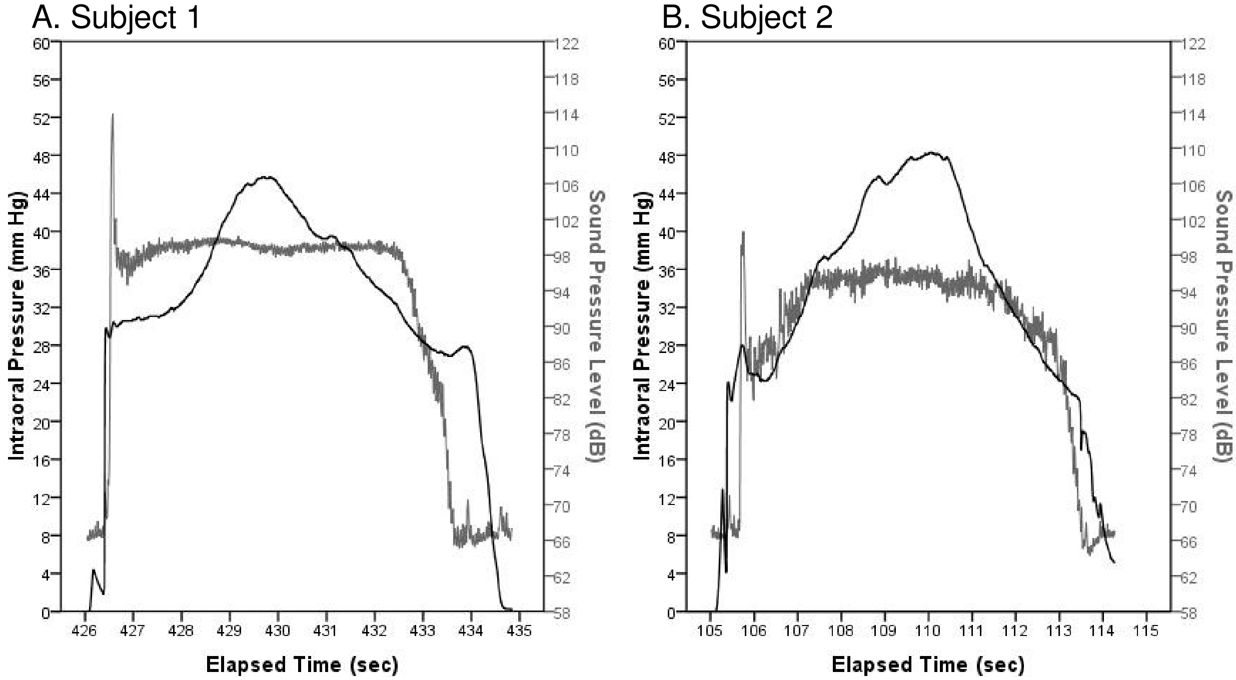
Figure 7. Pitch D4 – Dynamic Contrast

Table 2. Pitch D4 – Dynamic Contrast

		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	596	33.683	(3.746)	26.365 - 40.352	92.592	(3.925)	76.499 - 98.305
2	532	35.150	(7.857)	23.642 - 45.551	97.440	(1.661)	88.273 - 99.529
3A	542	33.003	(1.837)	30.574 - 37.010	97.523	(1.525)	79.184 - 99.435
3B	515	34.262	(0.875)	32.678 - 36.391	97.397	(1.717)	81.303 - 99.529
4A	590	29.139	(3.572)	23.766 - 34.534	96.558	(2.996)	76.217 - 98.917
4B	641	31.118	(3.009)	24.384 - 34.782	97.766	(1.500)	81.915 - 99.435
All	3416	32.625	(4.553)	23.642 - 45.551	96.510	(3.048)	76.217 - 99.529

Figure 8 shows line graphs of all individual performances of the pitch G4, and table 3 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all G4 performances. Subject 4B did not perform this pitch.

A. Subject 1 B. Subject 2



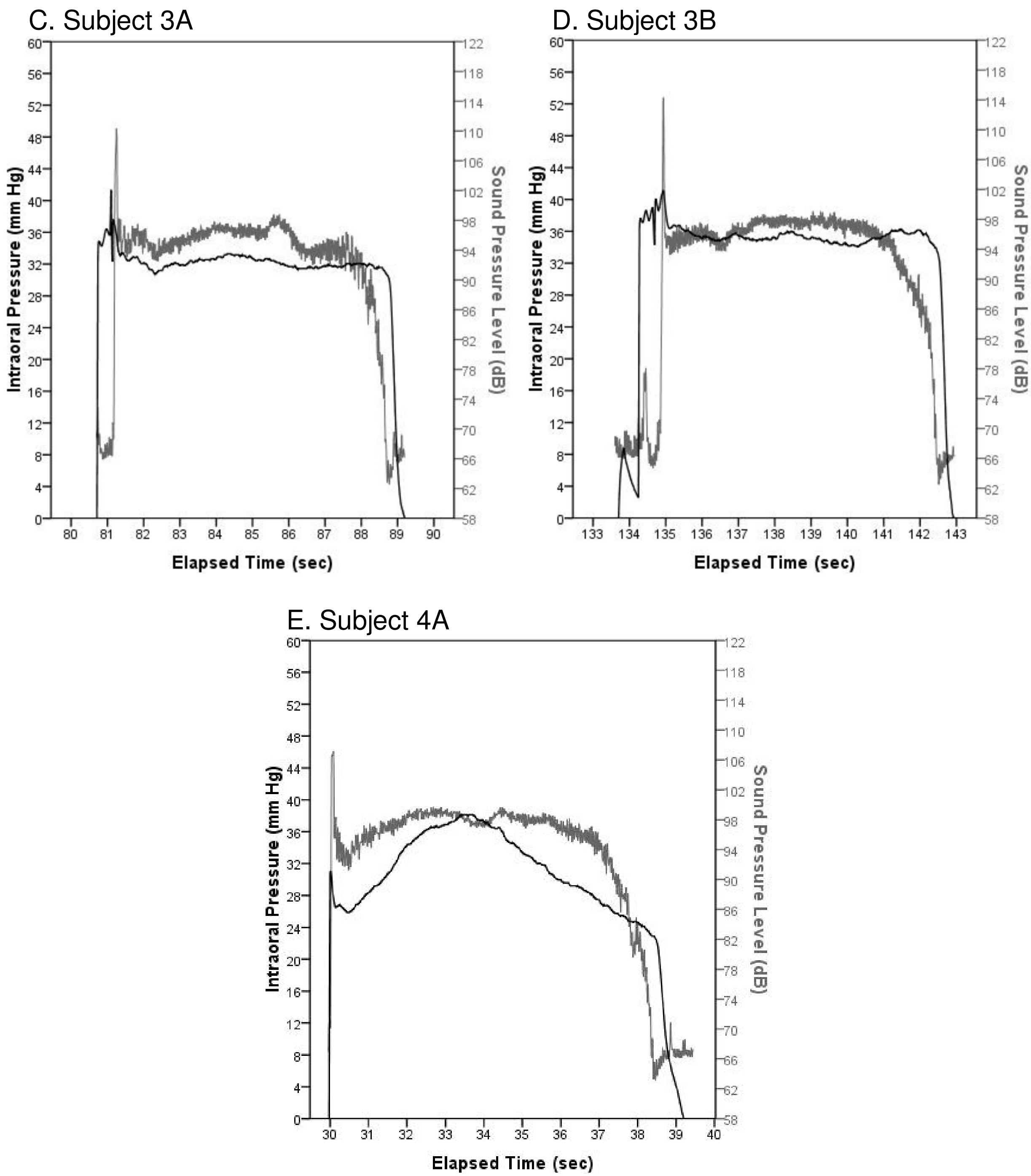
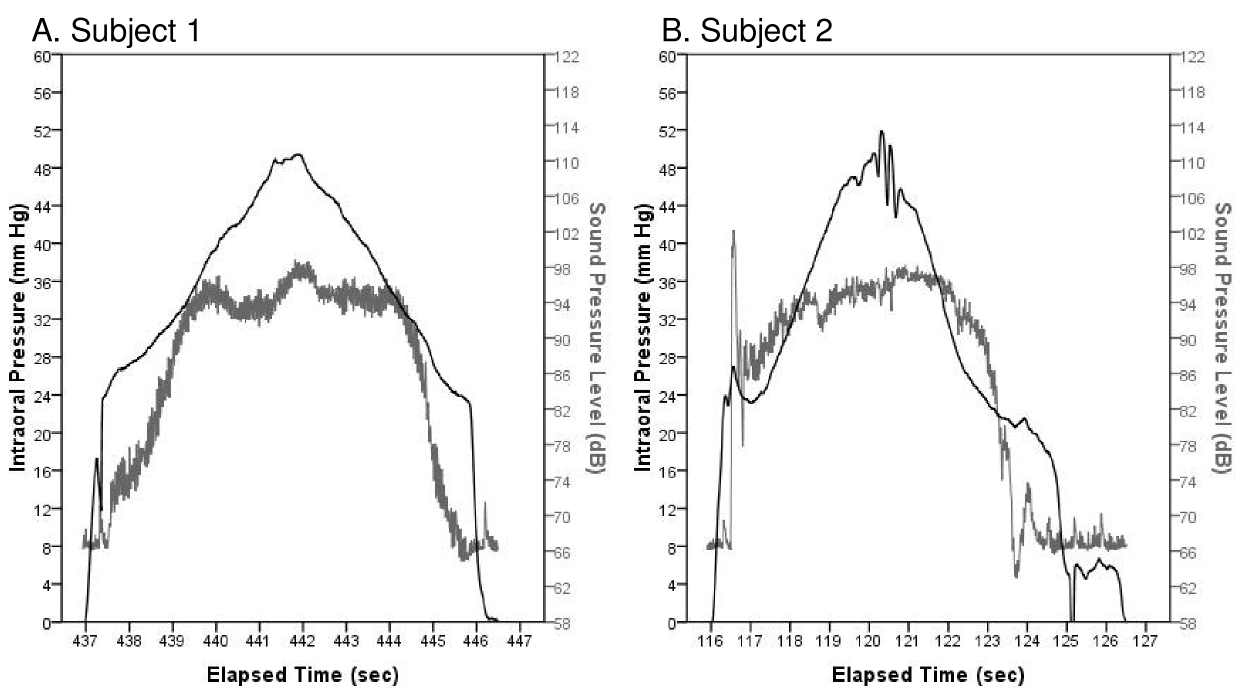


Figure 8. Pitch G4 – Dynamic Contrast

Table 3. Pitch G4 – Dynamic Contrast

Subject:	*n*	IOP (mm Hg) $\bar{x}$	(SD)	Range	SPL (dB) $\bar{x}$	(SD)	Range
1	545	36.184	(5.683)	26.984 – 45.674	97.219	(4.511)	74.003 – 100.140
2	591	36.429	(8.344)	22.776 – 48.274	92.637	(4.152)	73.438 – 97.786
3A	581	32.132	(0.580)	30.697 – 33.420	94.426	(3.645)	74.097 – 98.776
3B	582	35.285	(0.600)	34.039 – 36.762	95.246	(3.913)	74.662 – 99.058
4A	638	31.535	(4.423)	23.147 – 38.124	95.439	(5.213)	71.695 – 99.717
4B	N/A	N/A	N/A	N/A	N/A	N/A	N/A
All	2937	34.243	(5.358)	22.776 - 48.274	94.967	(4.576)	71.695 - 100.140

Figure 9 shows line graphs of all individual performances of the pitch C5, and table 4 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all C5 performances.



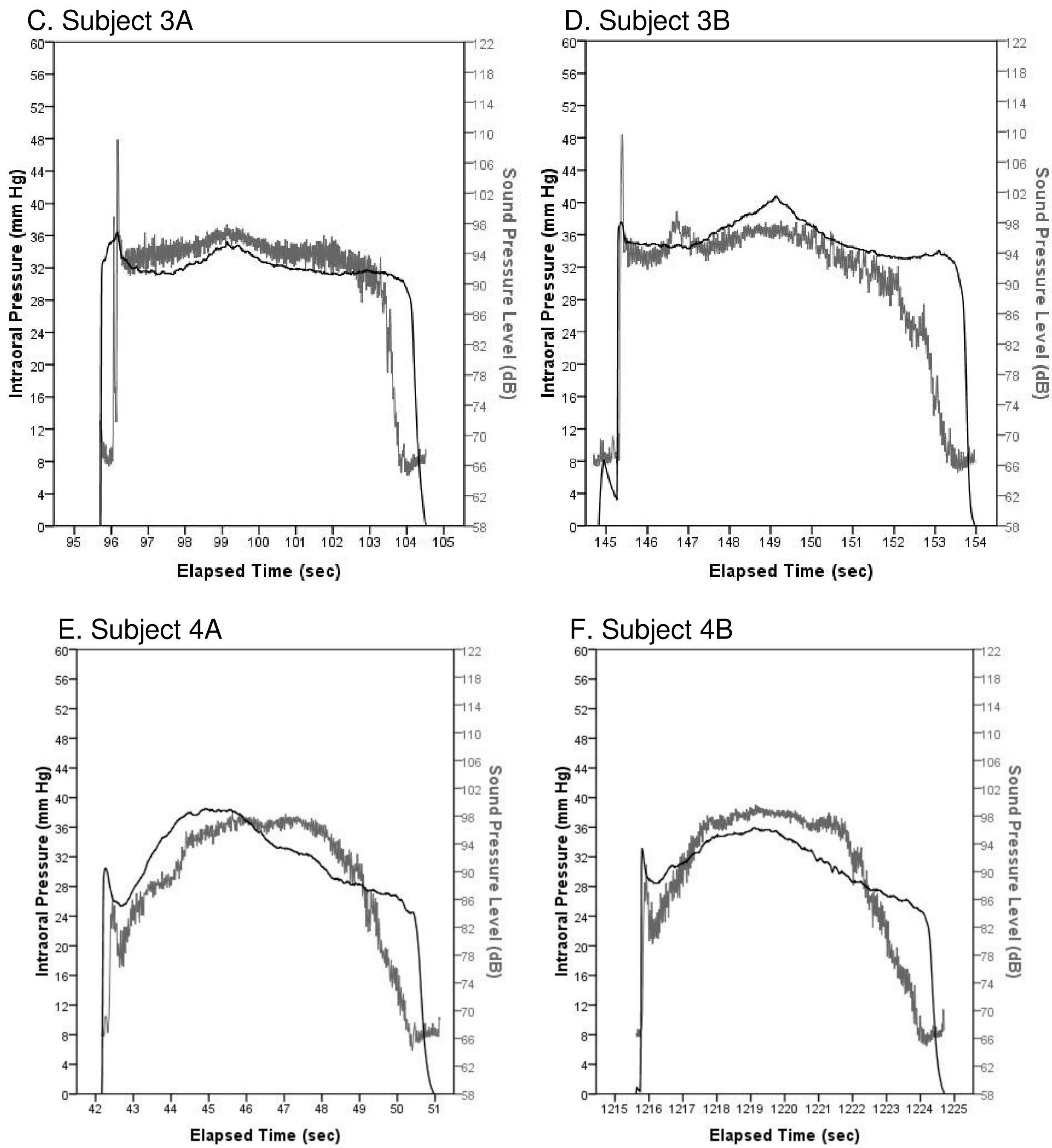


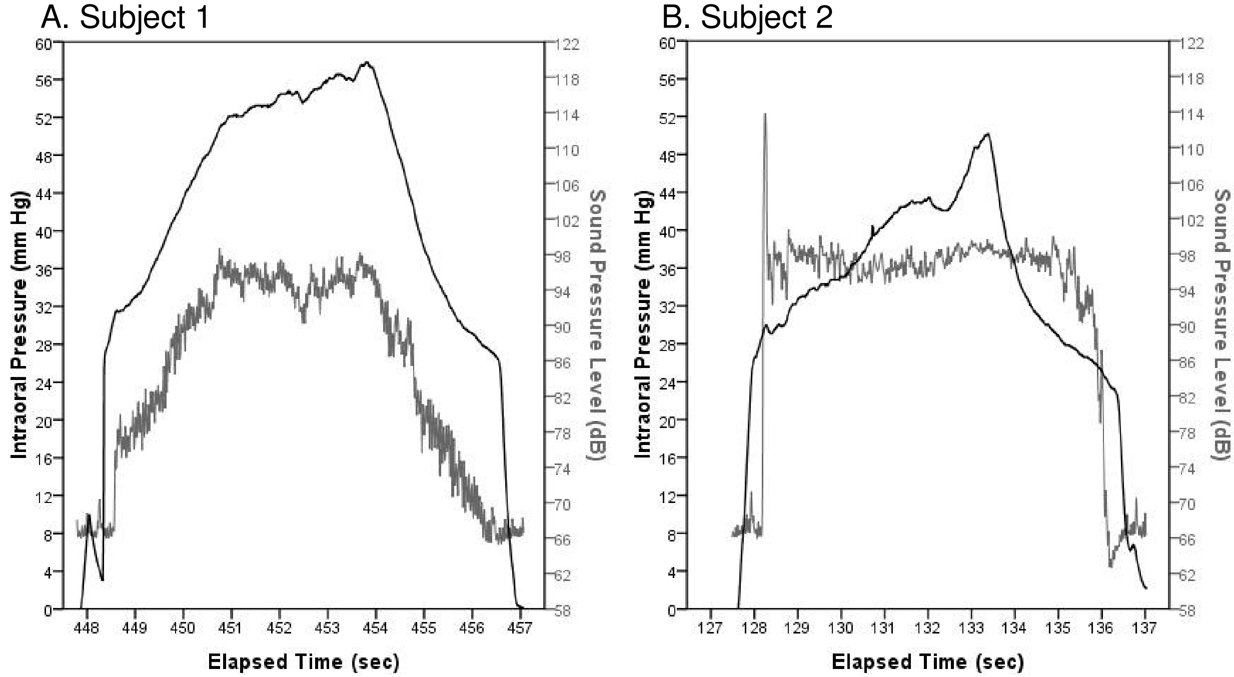
Figure 9. Pitch C5 – Dynamic Contrast

Table 4. Pitch C5 – Dynamic Contrast

		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	579	38.413	(7.030)	25.993 - 49.388	90.892	(6.850)	70.377 - 98.823
2	544	35.268	(9.511)	21.043 - 51.863	92.422	(4.942)	71.837 - 98.257
3A	586	32.241	(1.064)	31.069 - 35.153	93.749	(2.711)	78.195 - 97.881
3B	587	35.778	(2.115)	33.049 - 40.847	93.577	(3.829)	79.560 - 99.482
4A	525	33.283	(3.884)	25.375 - 38.495	92.942	(4.996)	76.217 - 98.446
4B	628	31.476	(3.207)	25.128 - 35.896	91.883	(7.672)	68.163 - 99.670
All	3449	34.376	(5.773)	21.043 - 51.863	92.568	(5.562)	68.163 - 99.670

Figure 10 shows line graphs of all individual performances of the pitch A5, and table 5 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all A5 performances.

A. Subject 1 B. Subject 2



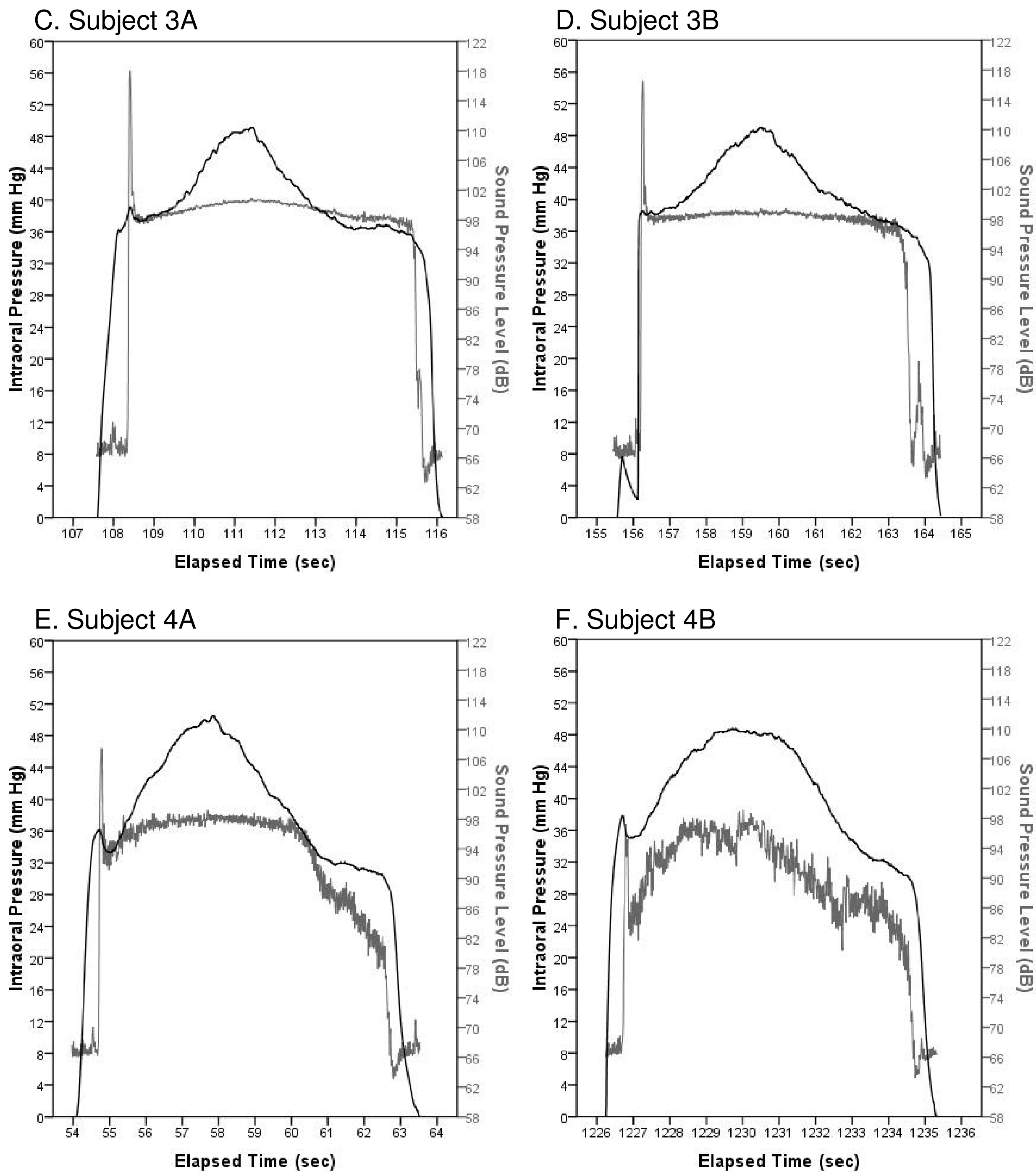


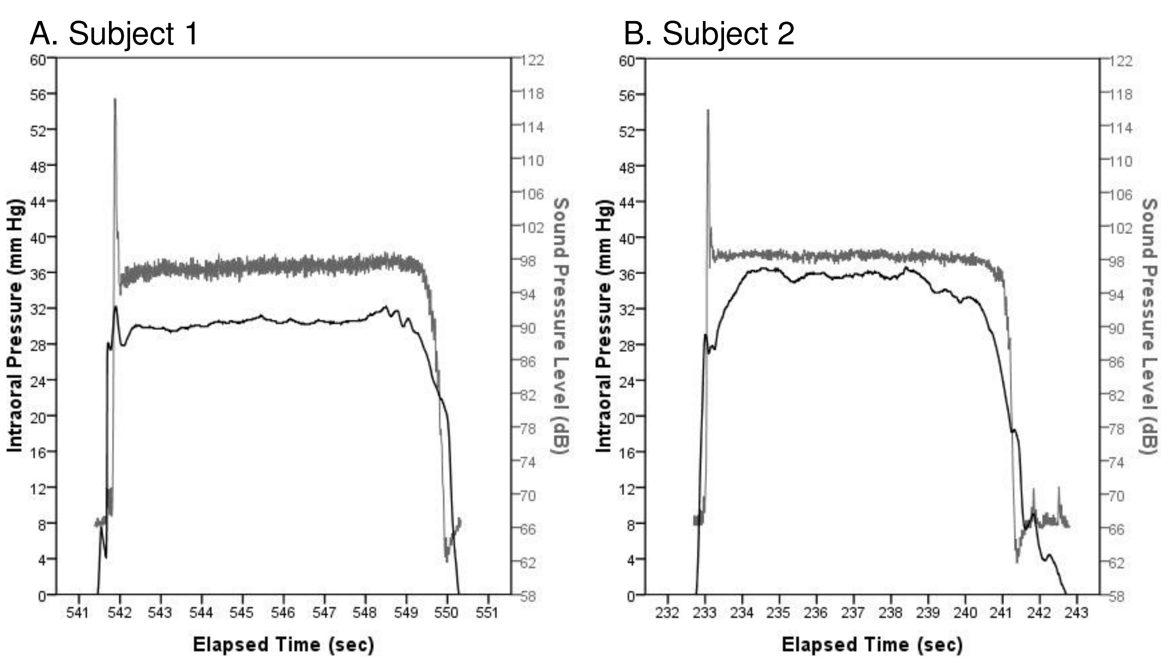
Figure 10. Pitch A5 – Dynamic Contrast

Table 5. Pitch A5 – Dynamic Contrast

Subject:	*n*	IOP (mm Hg) $\bar{x}$	(SD)	Range	SPL (dB) $\bar{x}$	(SD)	Range
1	622	45.490	(9.729)	27.355 - 57.805	87.585	(8.795)	65.526 - 98.681
2	620	36.624	(6.694)	24.632 - 50.130	96.629	(2.864)	74.003 - 100.710
3A	555	40.816	(4.360)	34.534 - 49.140	99.185	(1.126)	90.958 - 100.890
3B	573	41.954	(3.889)	35.895 - 49.017	98.076	(1.665)	80.173 - 99.482
4A	612	39.948	(6.668)	29.336 - 50.502	93.974	(5.631)	74.192 - 99.199
4B	616	41.209	(6.249)	29.707 - 48.769	90.798	(5.087)	74.286 - 99.152
All	3598	41.002	(7.124)	24.632 - 57.805	94.240	(6.482)	65.526 - 100.890

Task B

The experimental subjects produced a total of six performances of Task B: five with the laryngoscope in a superior position, and one with the laryngoscope in an inferior position (Subject 4B). Figure 11 shows line graphs of all individual straight tone (without vibrato) performances of the pitch D4.



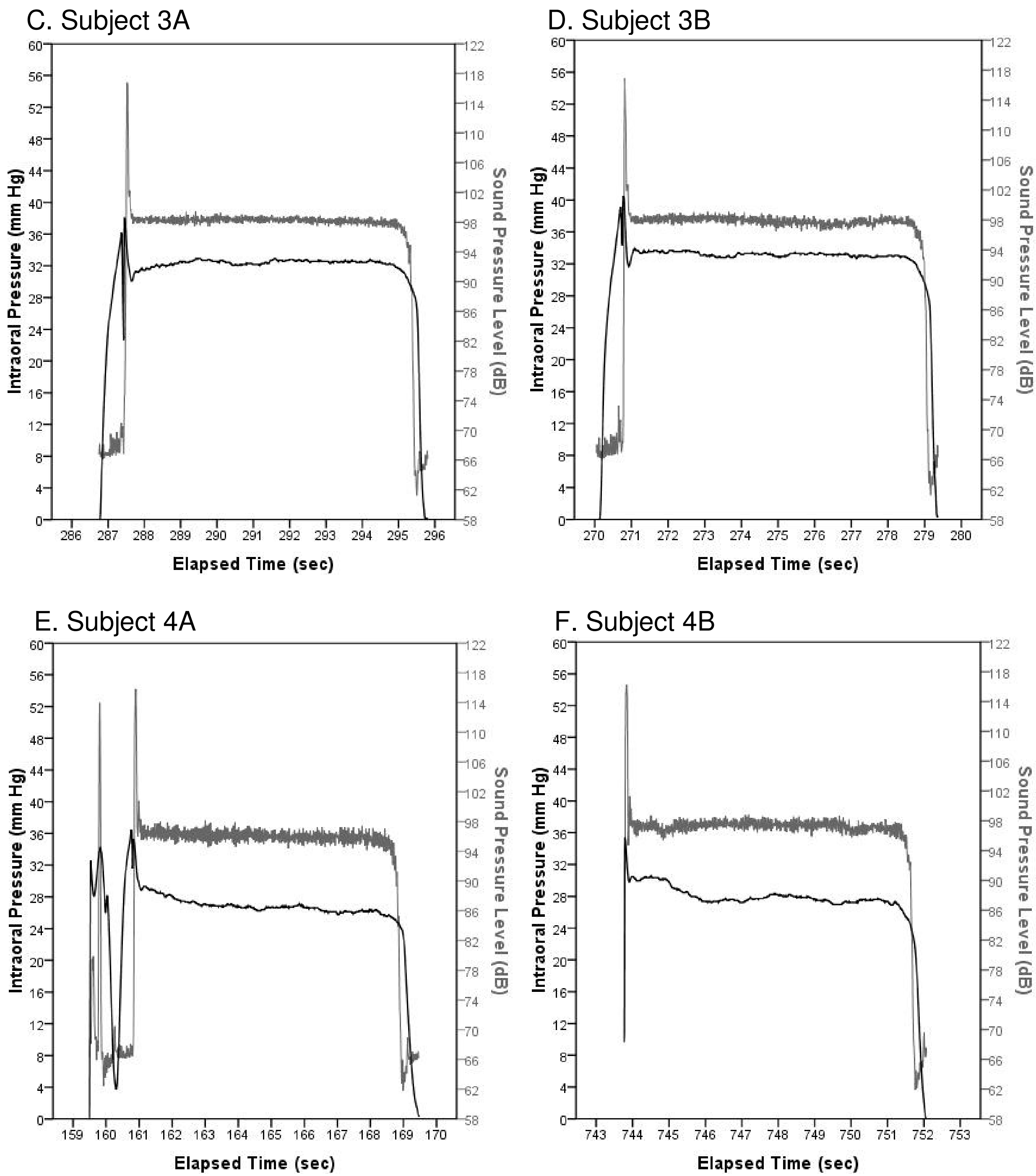


Figure 11. Pitch D4 – Straight Tone

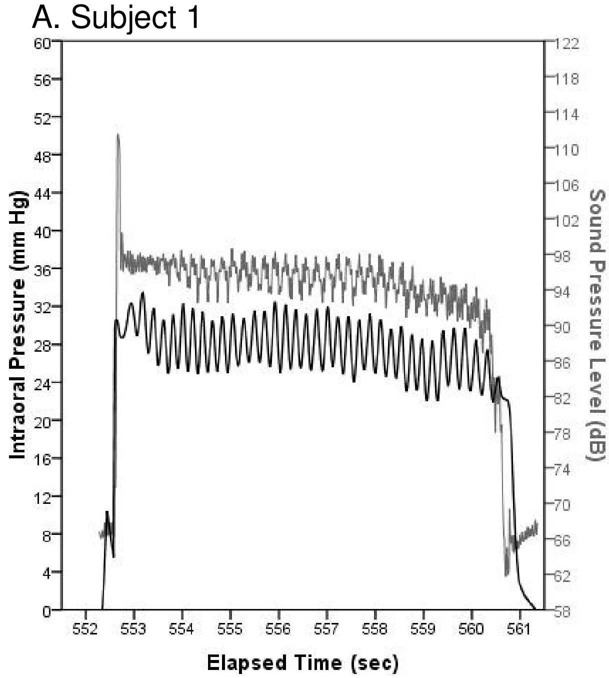
Table 6 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all straight-tone performances of pitch D4.

Table 6. Pitch D4 – Straight Tone

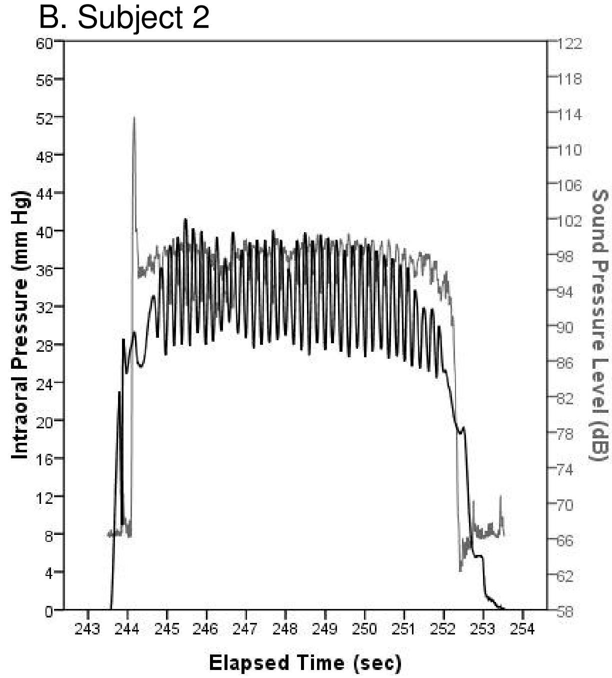
		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	560	30.395	(0.587)	28.346 - 32.183	97.074	(0.776)	95.196 - 98.870
2	575	34.969	(1.502)	28.841 - 36.638	98.343	(0.487)	96.468 - 99.341
3A	551	32.431	(0.266)	31.440 - 32.925	98.258	(0.398)	97.268 - 99.482
3B	579	33.182	(0.252)	32.678 - 33.668	97.887	(0.521)	96.468 - 99.105
4A	558	26.803	(0.663)	25.746 - 28.841	96.058	(0.742)	94.160 - 98.116
4B	549	27.940	(0.887)	26.860 - 30.574	97.331	(0.654)	95.432 - 98.870
All	3372	30.992	(3.001)	25.746 - 36.638	97.497	(0.997)	94.160 - 99.482

Figure 12 shows line graphs of all individual vibrato-tone performances of D4.

A. Subject 1



B. Subject 2



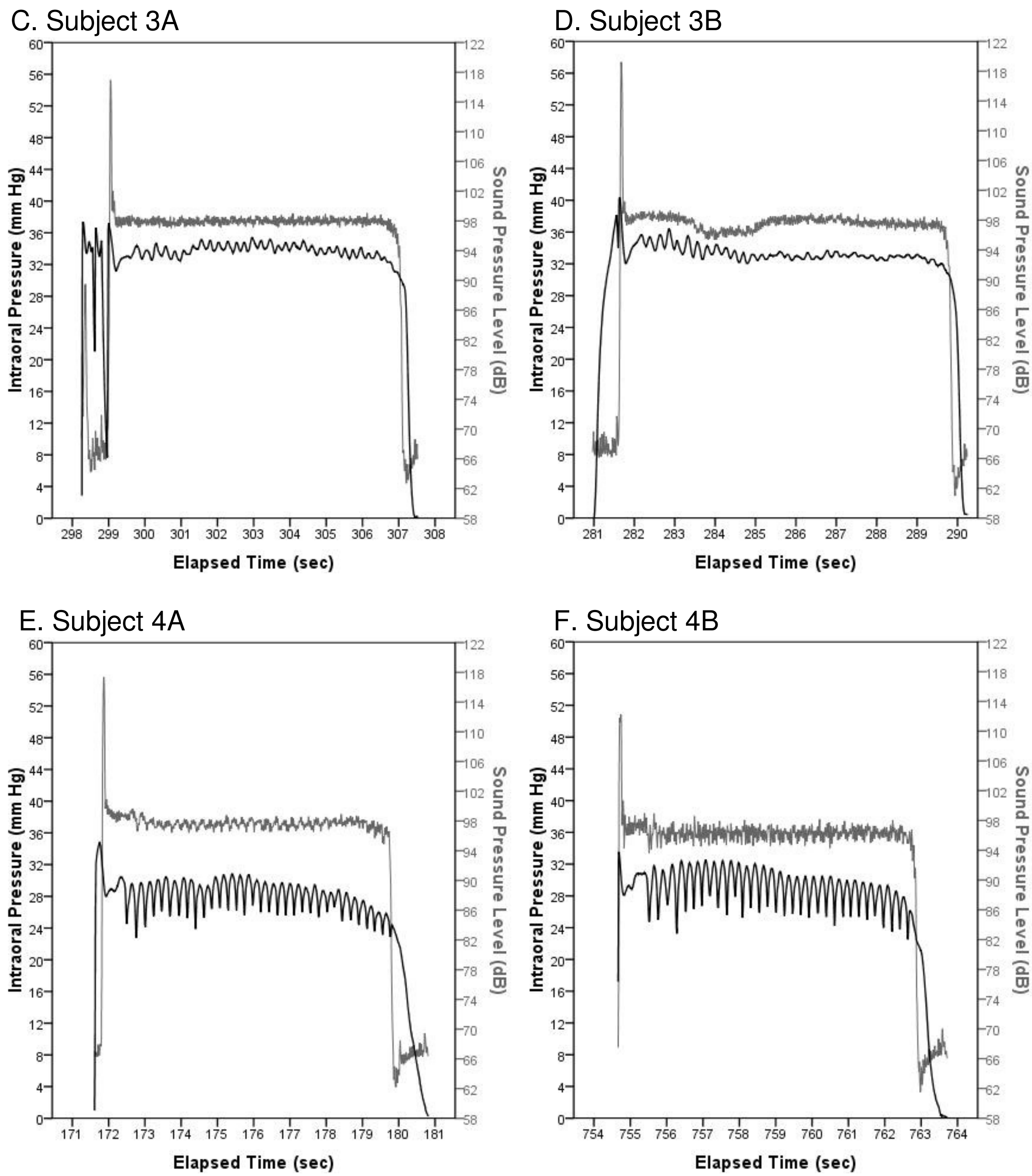


Figure 12. Pitch D4 – Vibrato Tone

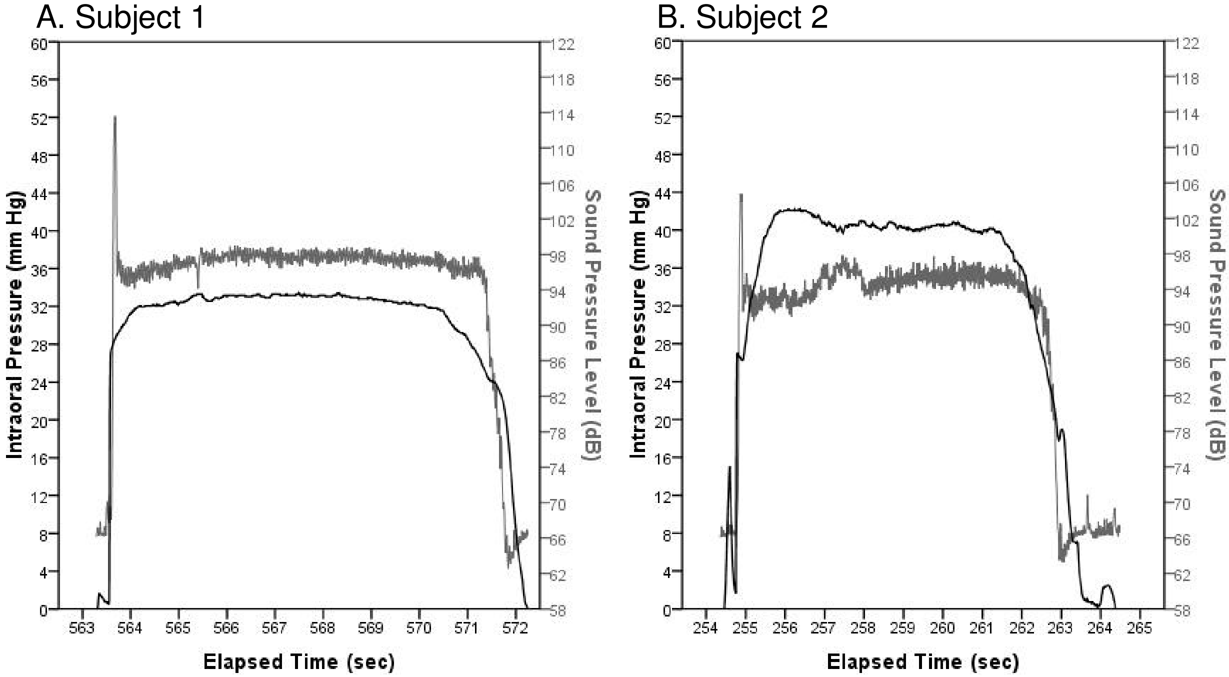
Table 7 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all vibrato-tone performances of pitch D4.

Table 7. Pitch D4 – Vibrato Tone

Subject:	n	IOP (mm Hg) $\bar{x}$	(SD)	Range	SPL (dB) $\bar{x}$	(SD)	Range
1	558	27.707	(2.414)	22.032 - 33.421	95.188	(1.846)	89.686 - 98.681
2	571	32.977	(4.155)	25.127 - 41.218	97.102	(1.786)	90.911 - 100.240
3A	563	33.835	(0.646)	32.430 - 35.400	97.970	(0.409)	97.033 - 99.058
3B	573	33.306	(0.812)	32.059 - 36.391	97.591	(0.809)	95.385 - 99.246
4A	555	28.209	(1.563)	22.775 - 30.821	97.695	(0.572)	96.374 - 99.670
4B	571	29.256	(1.952)	23.271 - 32.554	96.283	(0.835)	93.595 - 98.964
All	3391	30.901	(3.396)	22.032 - 41.218	96.973	(1.526)	89.686 - 100.240

Figure 13 shows line graphs of all individual straight-tone performances of pitch G4, and table 8 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all straight-tone G4 performances.

A. Subject 1 B. Subject 2



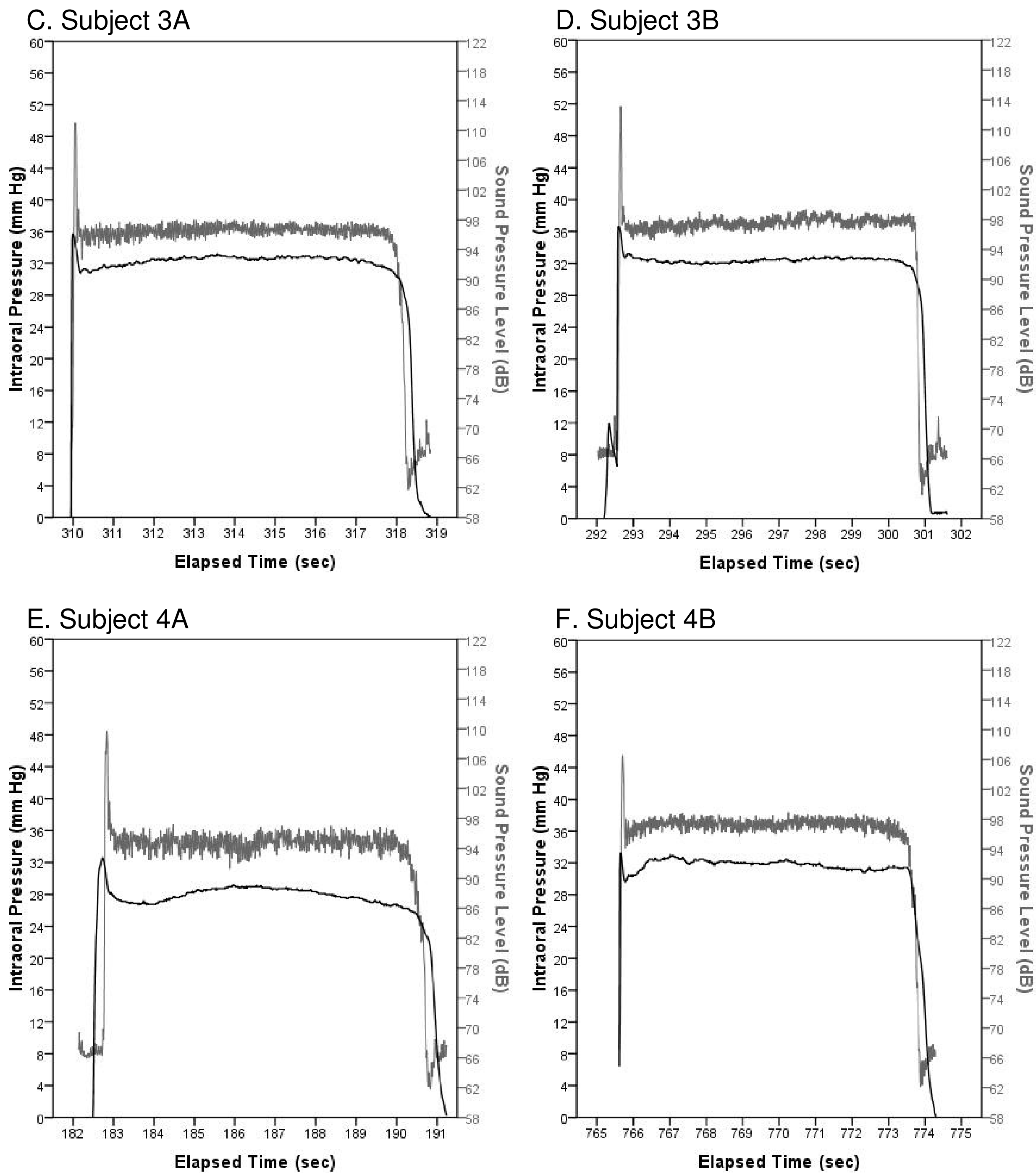


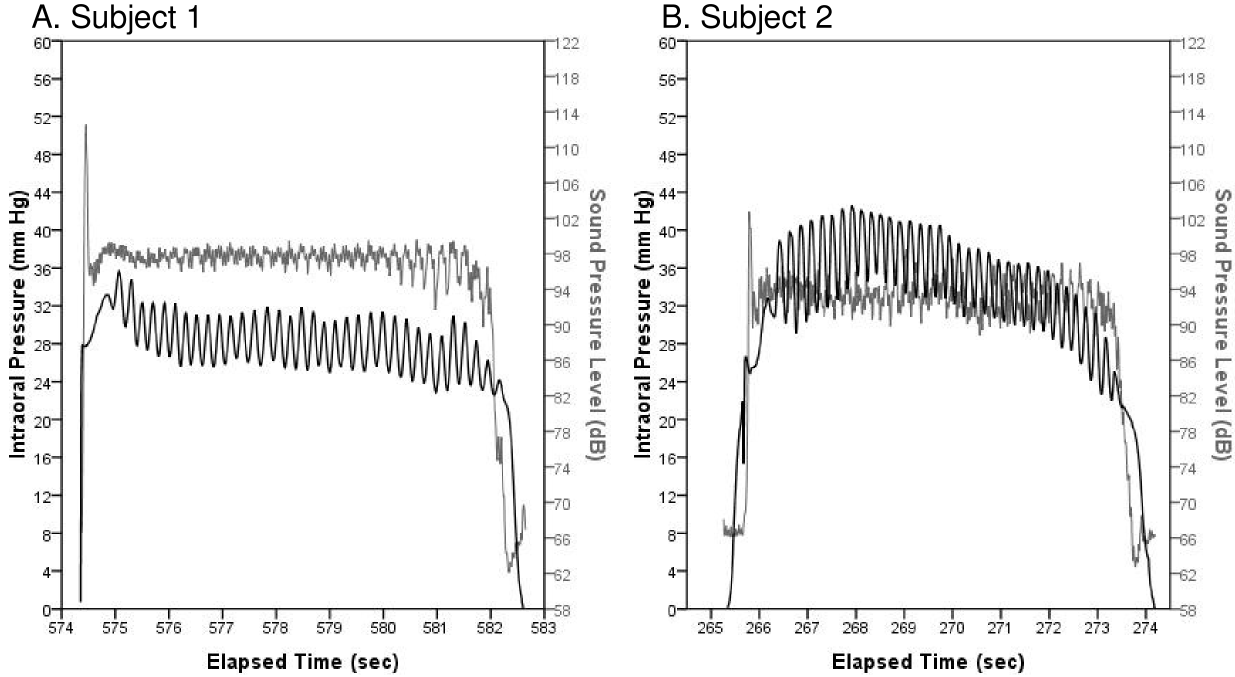
Figure 13. Pitch G4 – Straight Tone

Table 8. Pitch G4 – Straight Tone

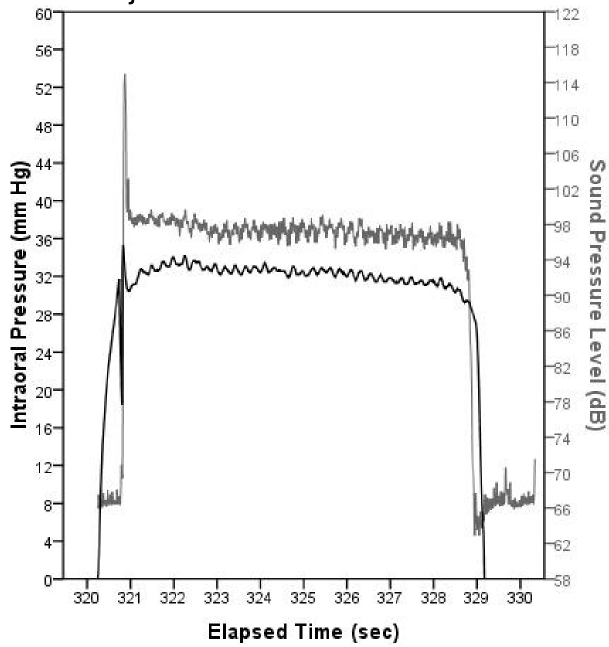
		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	564	32.377	(1.240)	26.860 - 33.421	97.343	(0.851)	94.160 - 99.011
2	559	40.017	(1.913)	30.697 - 42.209	94.792	(1.388)	90.863 - 97.834
3A	570	32.462	(0.433)	31.192 - 33.173	96.587	(0.735)	94.160 - 98.069
3B	573	32.376	(0.247)	31.811 - 32.802	97.536	(0.762)	95.196 - 99.294
4A	550	27.923	(0.820)	26.241 - 29.212	94.781	(1.088)	91.287 - 97.221
4B	565	31.853	(0.480)	30.821 - 32.925	97.326	(0.716)	95.008 - 98.917
All	3377	32.849	(3.706)	26.241 - 42.209	96.409	(1.509)	90.863 - 99.294

Figure 14 shows line graphs of all individual vibrato-tone performances of pitch G4, and table 9 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all vibrato-tone G4 performances.

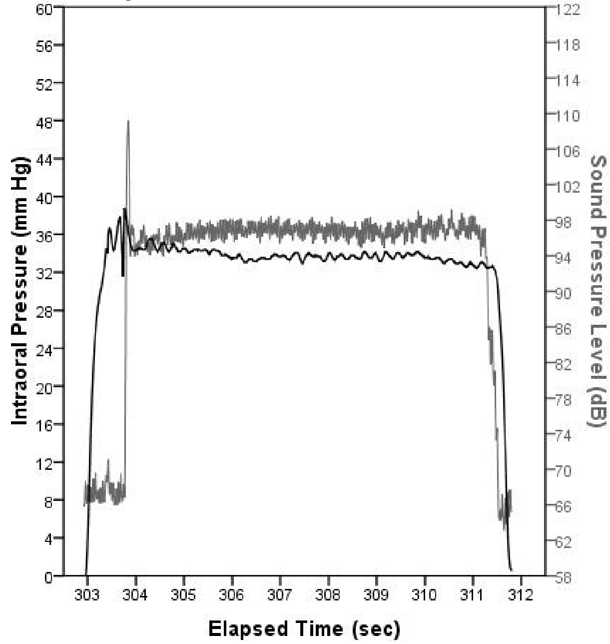
A. Subject 1 B. Subject 2



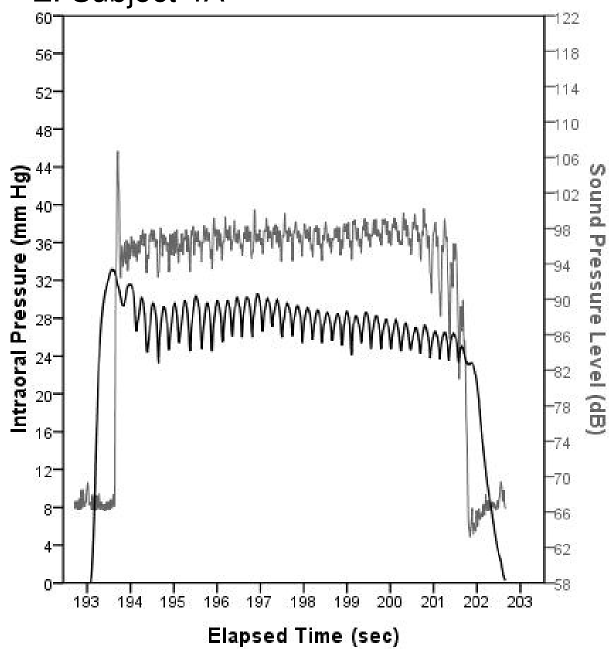
C. Subject 3A



D. Subject 3B



E. Subject 4A



F. Subject 4B

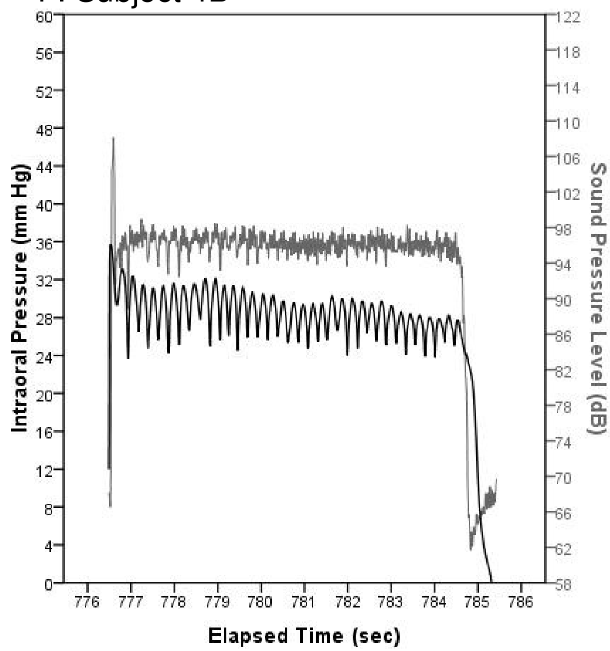


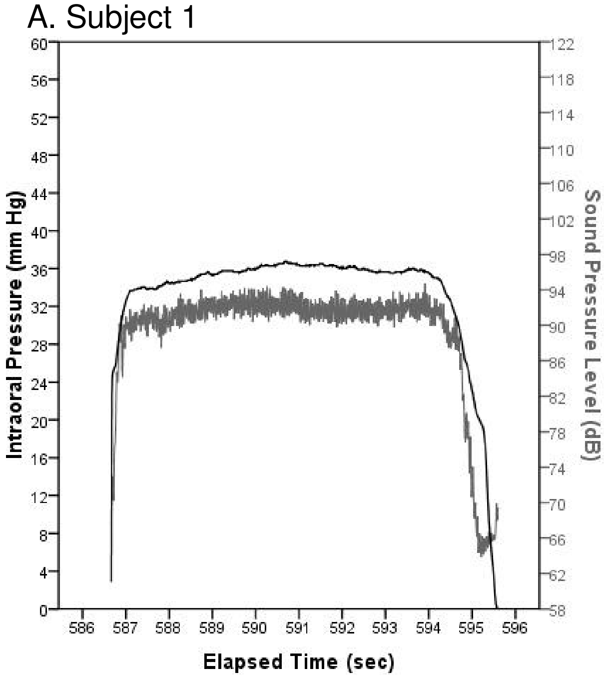
Figure 14. Pitch G4 – Vibrato Tone

Table 9. Pitch G4 – Vibrato Tone

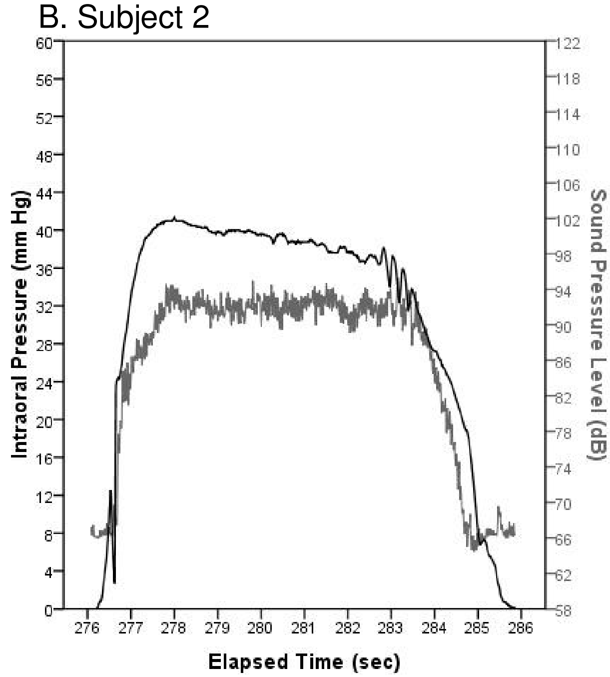
Subject:	*n*	IOP (mm Hg) $\bar{x}$	IOP (SD)	IOP Range	SPL (dB) $\bar{x}$	SPL (SD)	SPL Range
1	529	28.370	(2.490)	22.899 - 35.648	97.568	(1.069)	91.711 - 99.529
2	550	34.960	(4.311)	22.651 - 42.580	93.319	(1.696)	88.744 - 98.446
3A	560	32.383	(0.699)	30.697 - 34.163	97.319	(0.899)	95.149 - 99.670
3B	531	33.755	(0.483)	32.554 - 35.525	96.780	(0.869)	93.972 - 99.199
4A	566	27.594	(1.569)	23.270 - 30.574	96.847	(1.496)	88.085 - 100.240
4B	573	28.441	(1.784)	23.766 - 32.059	96.222	(1.014)	92.418 - 98.964
All	3309	30.888	(3.678)	22.651 - 42.580	96.337	(1.864)	88.085 - 100.240

Figure 15 shows line graphs of all individual straight-tone performances of pitch C5, and table 10 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all straight-tone C5 performances.

A. Subject 1



B. Subject 2



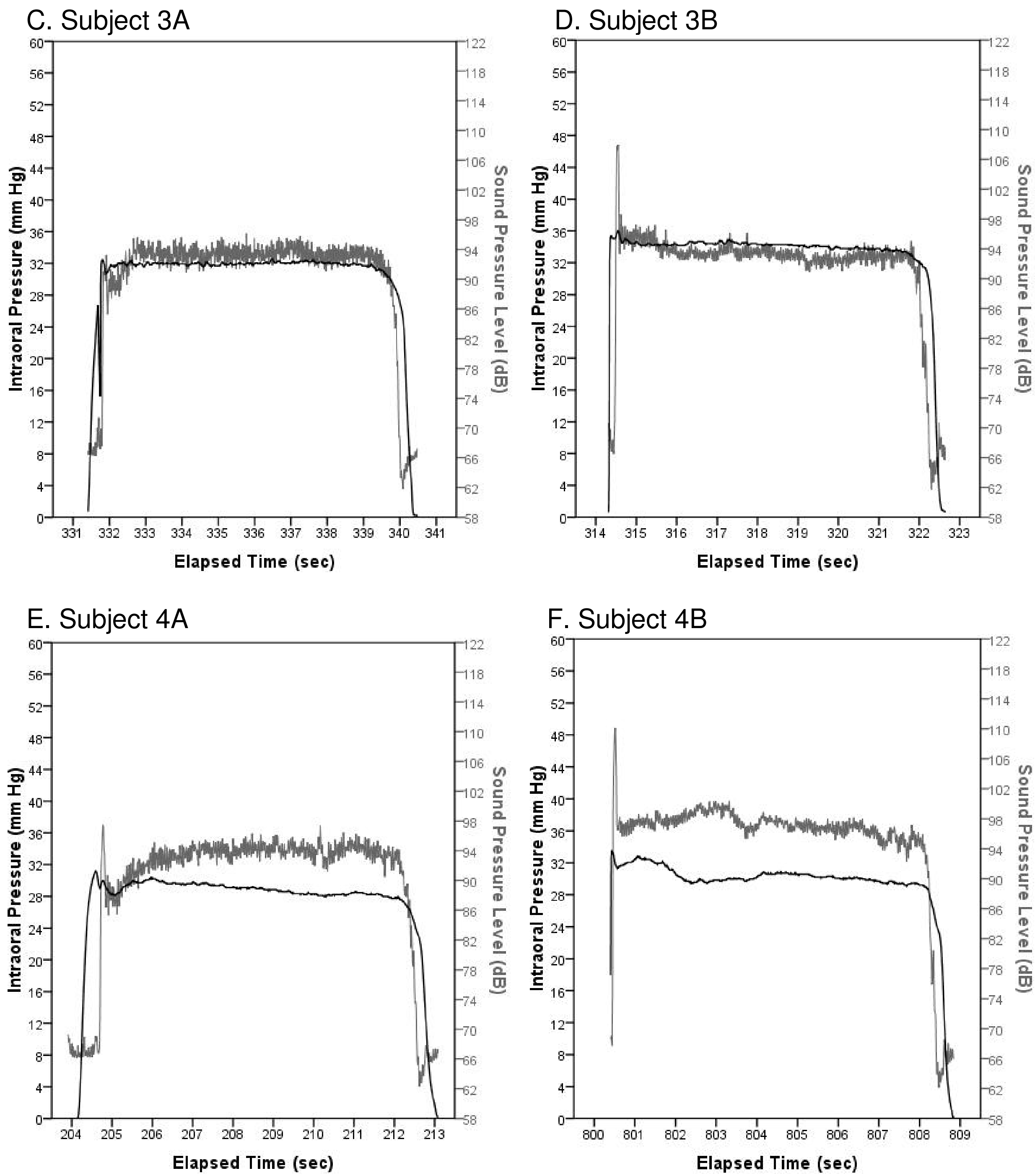
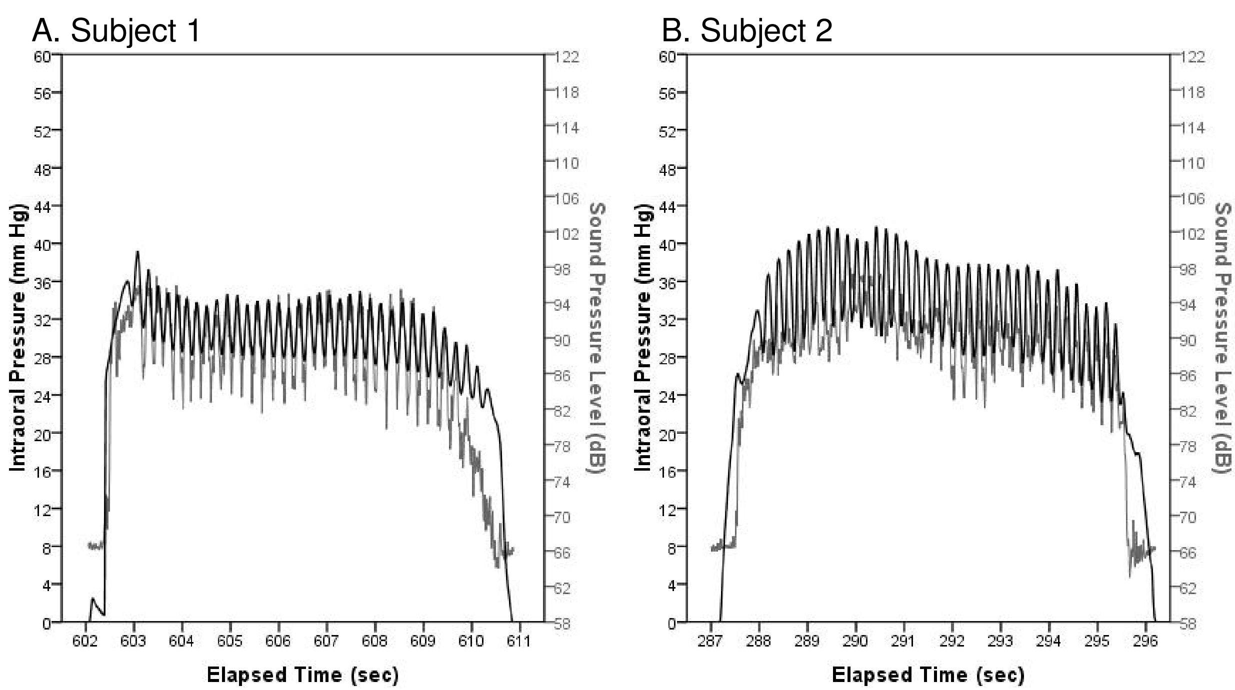


Figure 15. Pitch C5 – Straight Tone

Table 10. Pitch C5 – Straight Tone

		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	564	35.605	(0.756)	33.792 - 36.763	91.778	(1.171)	87.473 - 94.725
2	557	37.852	(3.265)	26.365 - 41.342	91.397	(2.036)	82.386 - 95.338
3A	563	31.954	(0.216)	31.069 - 32.554	93.394	(1.084)	89.309 - 96.185
3B	531	34.144	(0.326)	33.296 - 34.906	93.344	(1.055)	90.911 - 97.174
4A	538	28.938	(0.658)	27.727 - 30.325	93.636	(1.381)	88.556 - 97.410
4B	543	30.321	(0.815)	29.088 - 32.801	97.273	(1.352)	92.276 - 100.380
All	3296	33.167	(3.390)	26.365 - 41.342	93.450	(2.352)	82.386 - 100.380

Figure 16 shows line graphs of all individual vibrato-tone performances of pitch C5, and table 11 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all vibrato-tone C5 performances.



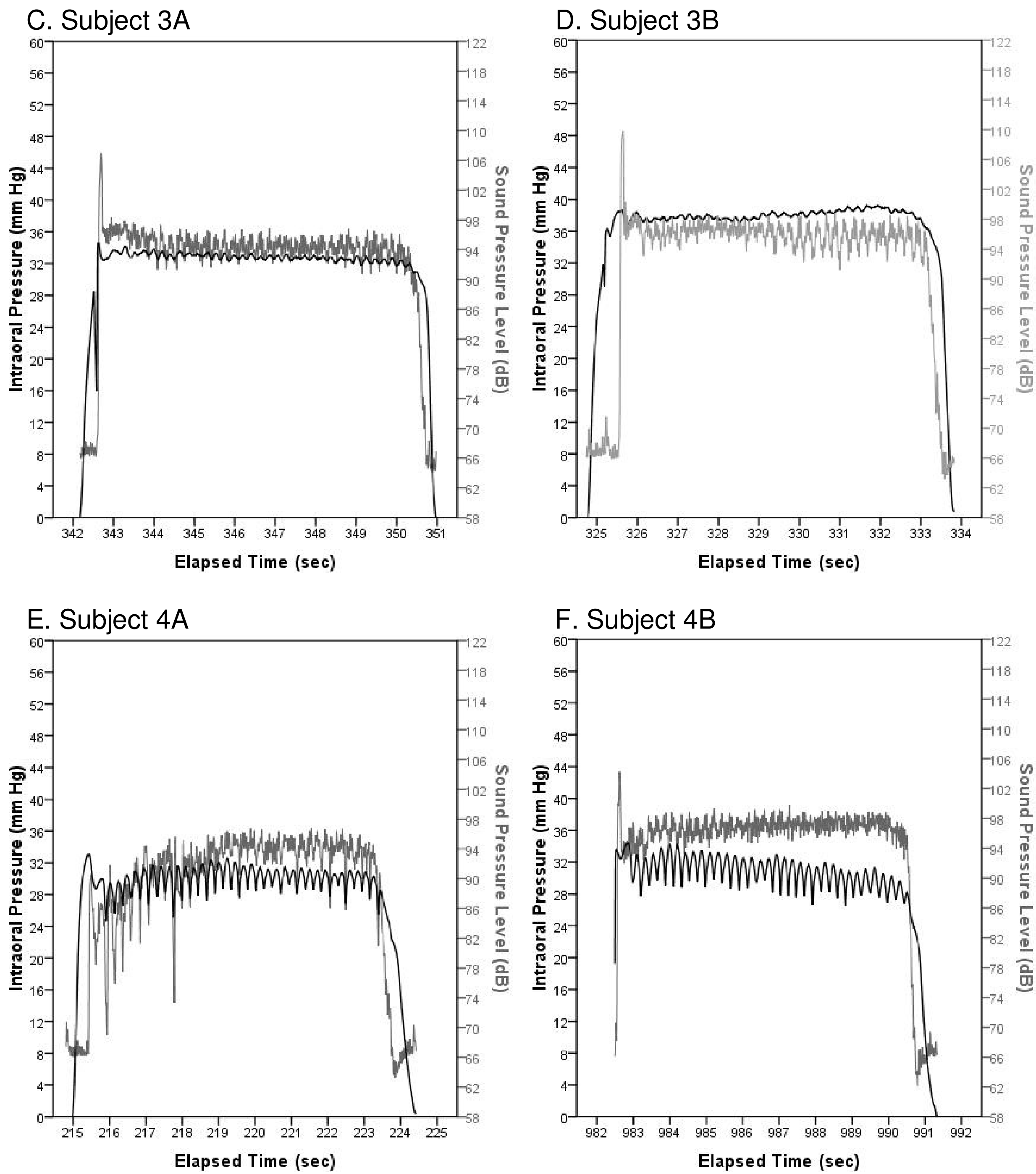
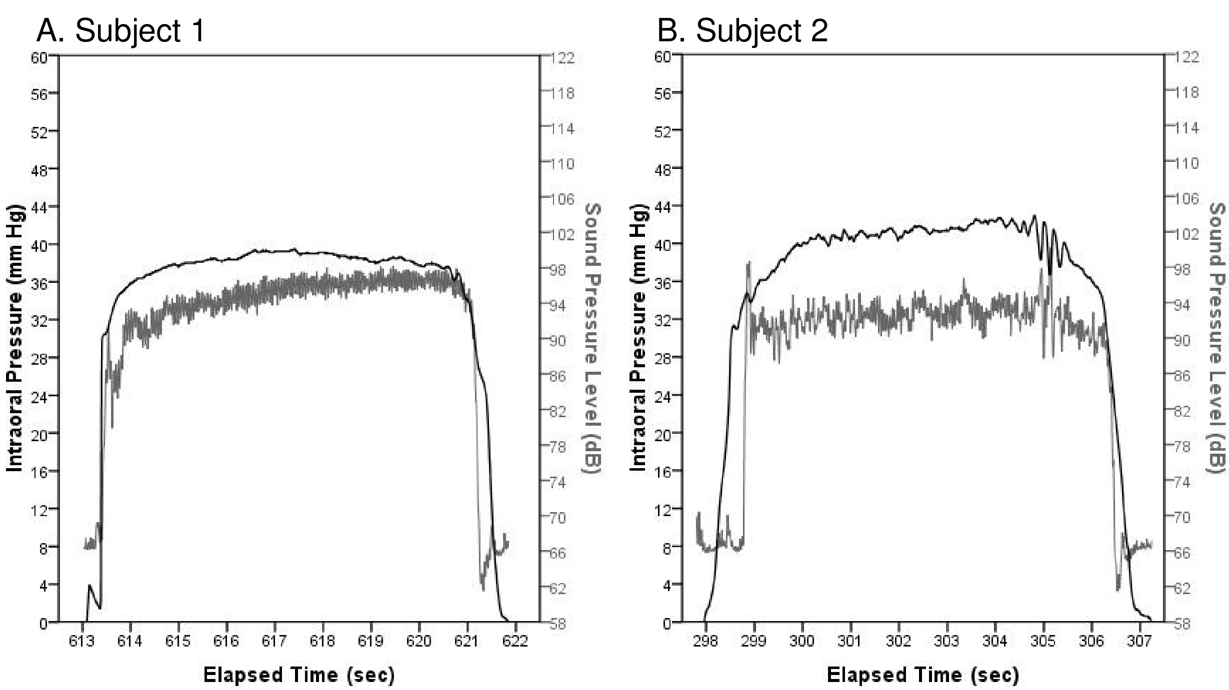


Figure 16. Pitch C5 – Vibrato Tone

Table 11. Pitch C5 – Vibrato Tone

		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	533	30.828	(2.554)	25.004 - 39.114	89.485	(3.975)	77.488 - 96.986
2	567	33.778	(4.104)	23.271 - 41.713	90.373	(3.280)	80.173 - 97.834
3A	555	32.799	(0.419)	31.687 - 34.163	94.437	(1.307)	90.722 - 97.928
3B	530	38.078	(0.529)	37.133 - 39.238	96.025	(1.339)	91.146 - 98.964
4A	566	30.100	(1.254)	25.128 - 32.554	92.263	(3.589)	73.297 - 96.703
4B	561	30.878	(1.584)	26.489 - 34.287	96.836	(1.203)	92.135 - 99.765
All	3312	32.708	(3.436)	23.271 - 41.713	93.233	(3.861)	73.297 - 99.765

Figure 17 shows line graphs of all individual straight-tone performances of pitch A5, and table 12 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all straight-tone A5 performances.



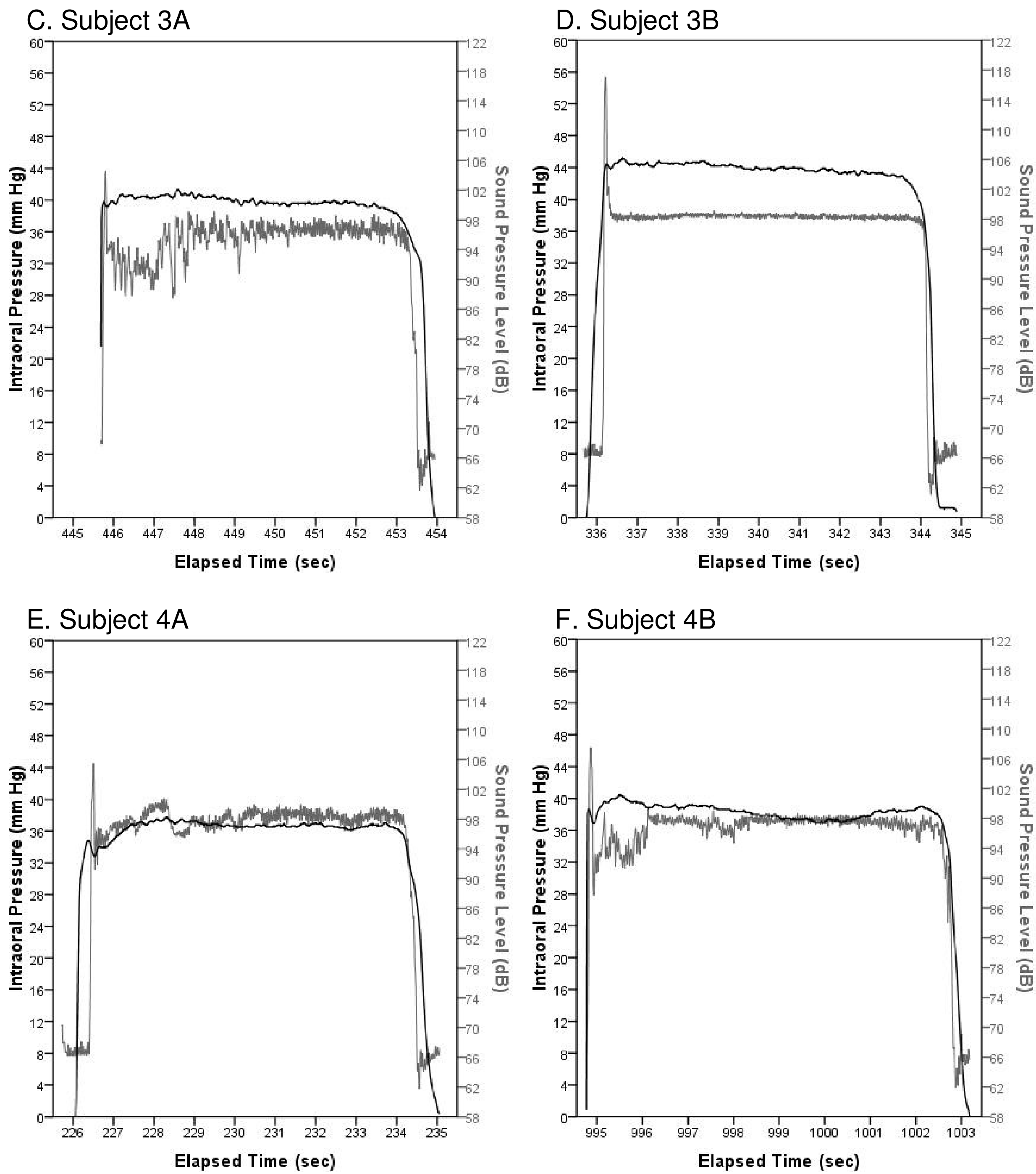


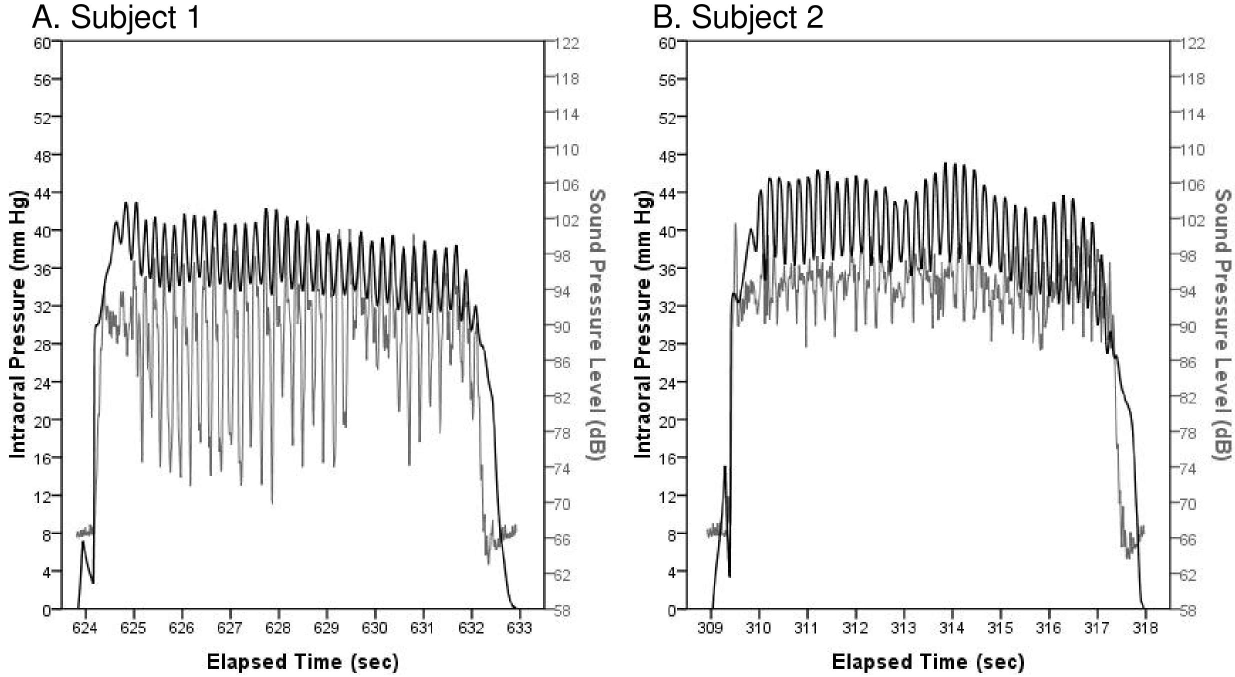
Figure 17. Pitch A5 – Straight Tone

Table 12. Pitch A5 – Straight Tone

		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	533	38.296	(0.749)	35.896 - 39.485	95.096	(1.867)	88.838 - 98.210
2	522	40.707	(1.451)	36.391 - 42.951	92.551	(1.642)	87.143 - 100.190
3A	536	39.891	(0.555)	38.371 - 41.342	95.676	(2.298)	87.473 - 99.105
3B	554	43.903	(0.534)	42.456 - 44.808	98.360	(0.264)	97.692 - 99.105
4A	556	36.726	(0.398)	34.906 - 37.753	98.114	(1.044)	95.479 - 100.800
4B	555	38.351	(0.807)	37.009 - 40.475	97.143	(1.343)	91.193 - 99.341
All	3256	39.640	(2.446)	34.906 - 44.808	96.203	(2.515)	87.143 - 100.800

Figure 18 shows line graphs of all individual vibrato-tone performances of pitch A5, and table 13 reports descriptive statistics for the intraoral pressure and sound pressure measurements collected during all vibrato-tone A5 performances.

A. Subject 1 B. Subject 2



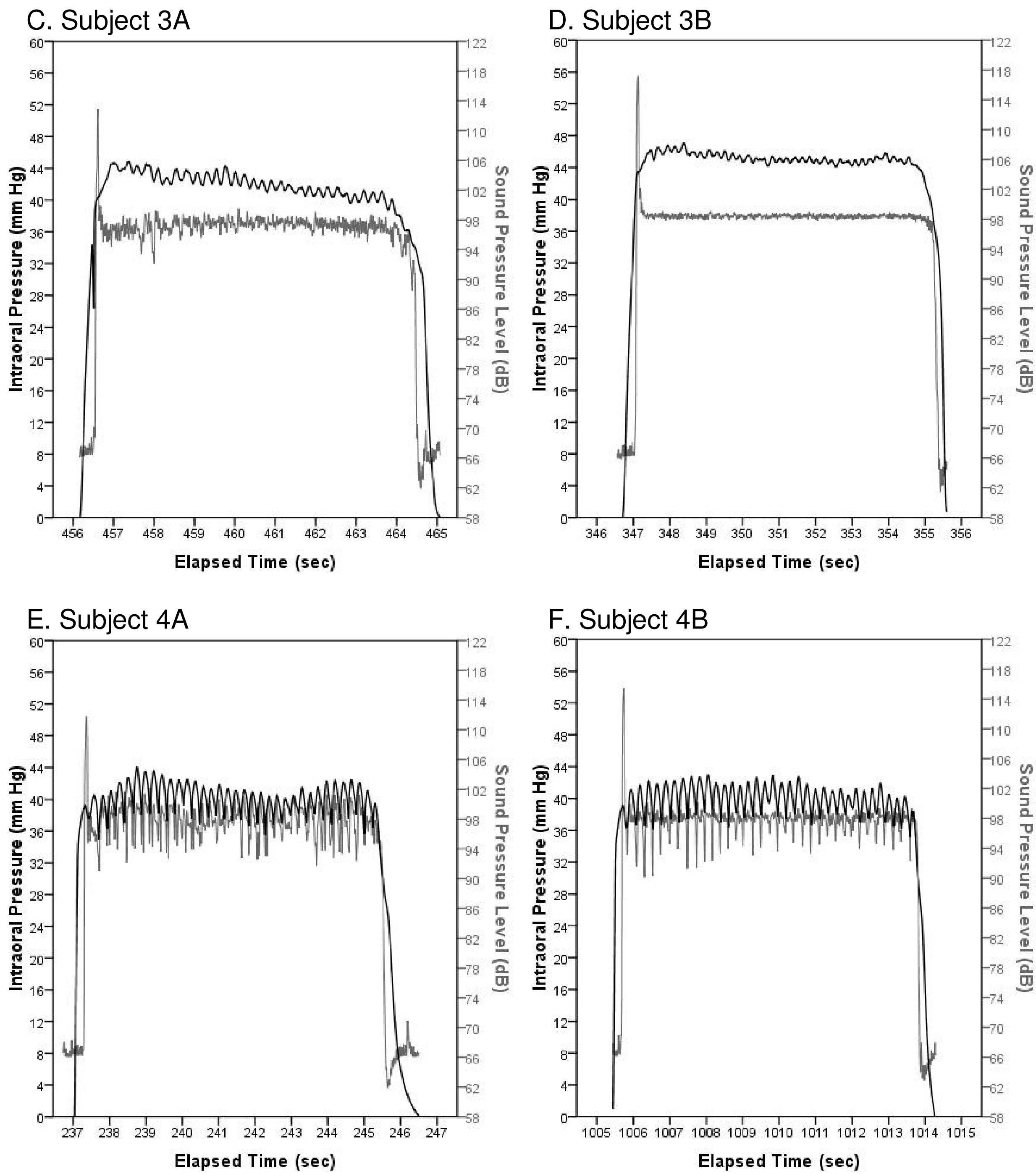


Figure 18. Pitch A5 – Vibrato Tone

Table 13. Pitch A5 – Vibrato Tone

		IOP (mm Hg)			SPL (dB)		
Subject:	*n*	$\bar{x}$	(SD)	Range	$\bar{x}$	(SD)	Range
1	543	36.670	(2.756)	31.192 - 42.951	88.836	(7.170)	69.812 - 102.780
2	550	40.140	(3.715)	31.812 - 47.160	94.614	(2.490)	87.143 - 100.090
3A	549	41.986	(1.359)	38.495 - 44.808	97.269	(0.946)	92.182 - 99.529
3B	575	45.178	(0.600)	44.065 - 47.036	98.398	(0.245)	97.692 - 99.058
4A	574	40.196	(1.604)	35.524 - 44.065	97.825	(2.024)	91.711 - 102.170
4B	567	40.059	(1.527)	36.144 - 42.952	97.603	(1.447)	90.110 - 100.140
All	3358	40.739	(3.343)	31.192 - 47.160	95.815	(4.621)	69.812 - 102.780

CHAPTER 5

DISCUSSION OF RESULTS

Characterization of Individual Pitches

The straight-tone data from Task B describe the general properties of the four pitches studied in this experiment. The subjects played at a *mf* dynamic level chosen by them, holding each pitch as steady as possible. Table 14 shows the mean ($\bar{x}$) and standard deviation (SD) for intraoral pressure (IOP) and sound pressure (SPL) of each pitch (with all subjects aggregated).

Table 14. Straight Tone – $\bar{x}$ and SD – All Subjects

	IOP (mm Hg)		SPL (dB)	
	$\bar{x}$	(SD)	$\bar{x}$	(SD)
D4	30.992	(3.001)	97.497	(0.997)
G4	32.849	(3.706)	96.409	(1.509)
C5	33.167	(3.390)	93.450	(2.352)
A5	39.640	(2.446)	96.203	(2.515)
	Excluding Subject 2:			
D4	30.174	(2.544)	97.323	(0.986)
G4	31.427	(1.876)	96.730	(1.313)
C5	32.214	(2.508)	93.868	(2.187)
A5	39.437	(2.542)	96.900	(1.997)

Figure 19 plots the above data graphically. The mean IOP rises as pitch level rises, as expected, and a pitch's register appears to be an important factor in determining its IOP requirement. Among oboists, D4 is considered a low note, G4 and C5 are in the middle register, and A5 is a high note. Clearly the IOP required for middle notes is similar, and their status as middle-range pitches is more important than their distance from surrounding pitches. For example, the leap from D4 to G4 is a perfect fourth, and the mean IOP increases by approximately 2 millimeters of mercury (mm Hg) between these notes. However, the interval between G4 and C5 is another perfect fourth, but the mean IOP only increases by approximately 0.3 mm Hg for the higher note. The mean increase in IOP between C5 and A5 is much greater, approximately 6.5 mm Hg, showing the increased pressure required to play in the high register.

A. All Subjects Combined

B. Subject 2 Excluded

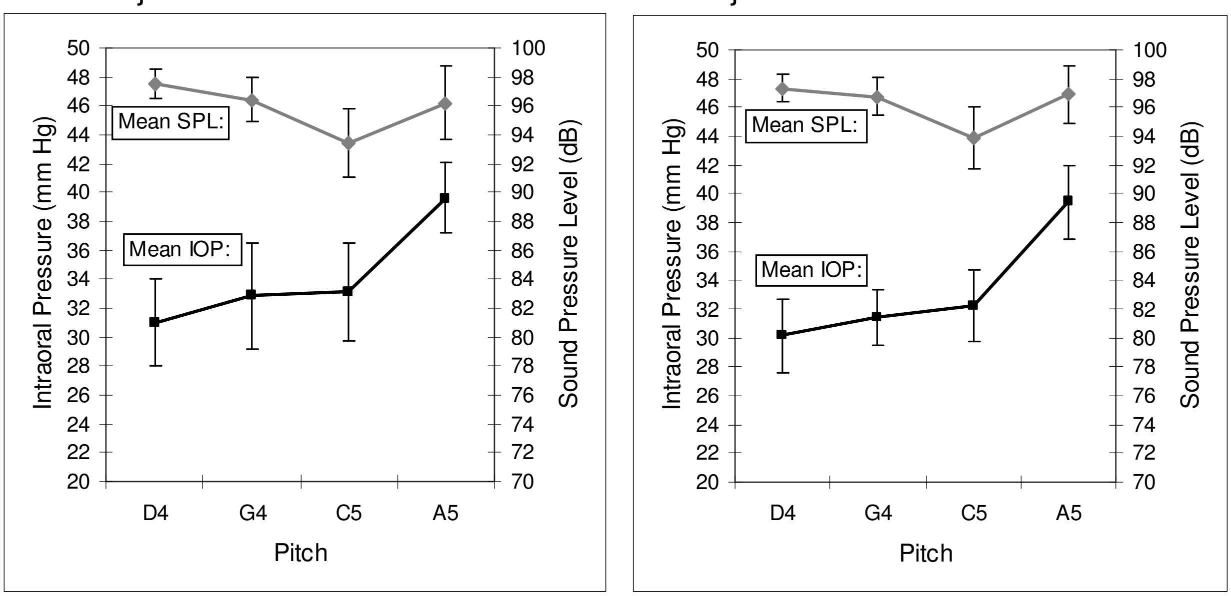


Figure 19. Straight Tone – $\bar{x}$ and SD – All Subjects

Interestingly, the mean SPL differed more than expected between pitches, as the players were asked to maintain a constant dynamic. D4 was played the loudest, probably due to the difficulty many players have in starting that pitch softly. G4 and A5 were played at a similar volume, but C5 was played softer than any other note. C5 is known to be a thin, nasal sounding note on the modern oboe, because the fingering for that pitch uses the shortest length of instrument (reducing the amount of wood or other material to color and warm the tone) and it uses a very small tone hole compared to its neighboring pitches. Oboists instinctively dampen or muffle C5 in actual performance to prevent it from standing out in a musical line. That is likely the case in Task B as well, although ideally in a true performance the oboist would use the smallest possible amount of dampening to avoid having C5 sound unusually soft compared to the adjacent pitches in the melody. Here, the mean SPL for C5 was approximately 3% smaller than the SPL used for G4 or A5.

As can be seen from tables 6-13 in chapter 4, Subject 2 typically had a much larger range and SD for all pitches of Task B. When analyzing the subject group in aggregate, the greater dispersion of Subject 2's measurements added skew to the all-subject descriptive statistics. The variation between Subject 2 and the rest of the subject population could be due to many factors that are of interest, such as instrument type, experience level, and different performance methodology; therefore, rather than excluding this data I have presented results both including and excluding Subject 2.

Figures 20 and 21 summarize the straight tone data for each pitch from Task B, including the data for all subjects. The reference lines on each plot indicate the mean SPL and IOP values reported for each pitch. The lowest pitches (D4 and G4; figure 20) show a much tighter fit around the mean than the highest pitches (C5 and A5; figure 21). This is probably related to the nonlinearity of the oboe's IOP-to-SPL relationship, which will be discussed further under "Sound Envelope," below.

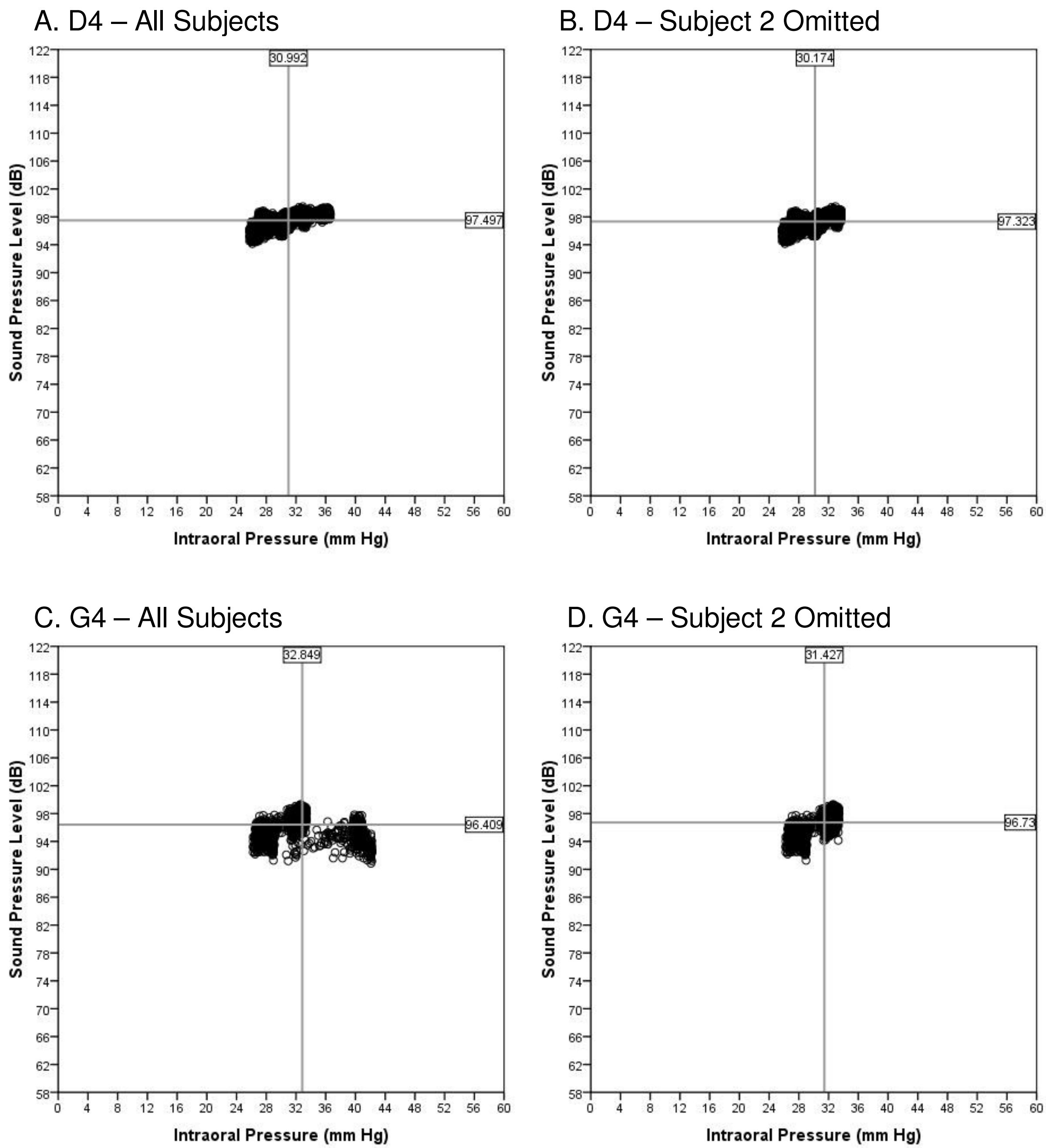


Figure 20. Pitches D4 and G4 (Straight) – SPL vs. IOP – All Subjects

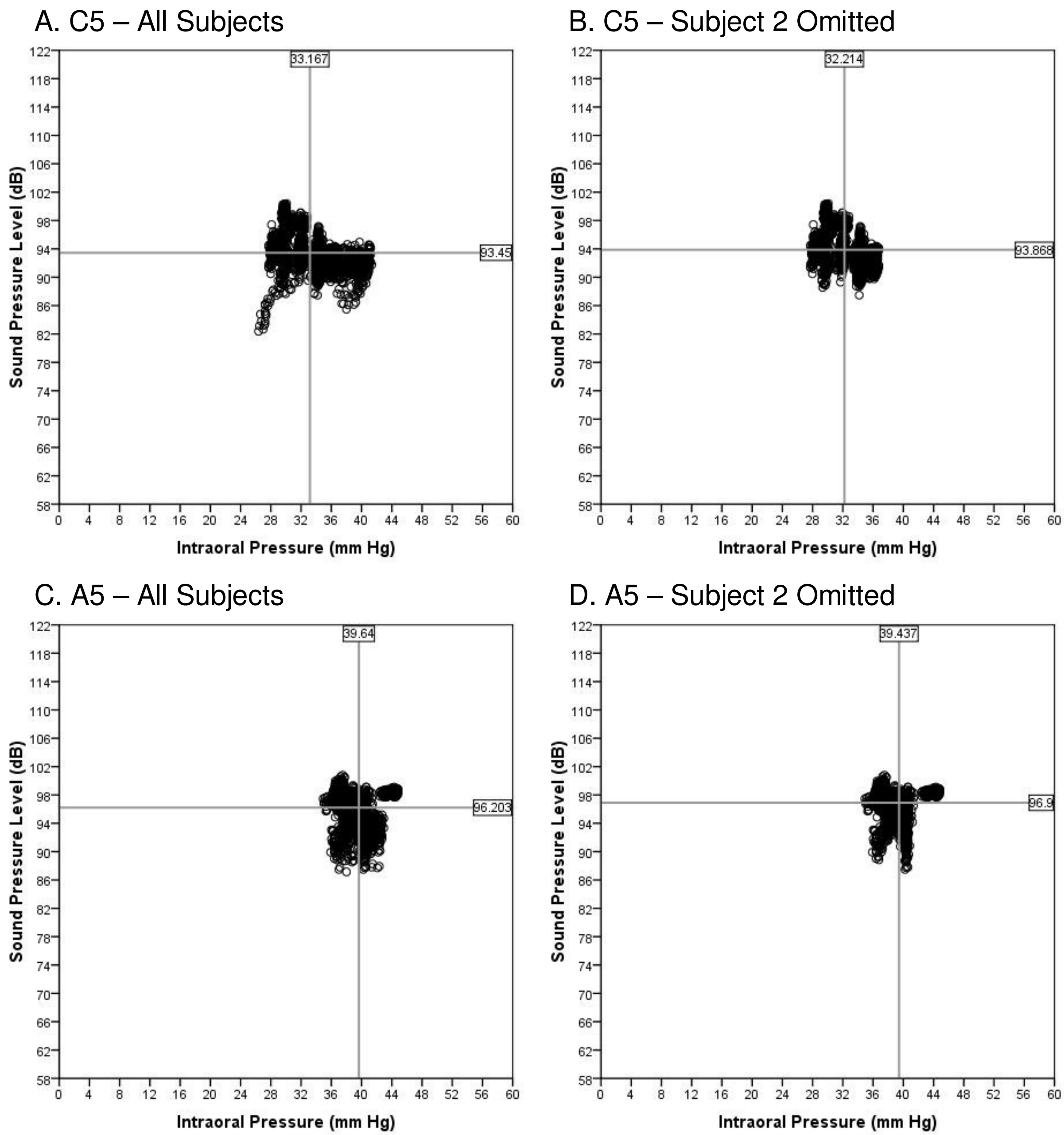


Figure 21. Pitches C5 and A5 (Straight) – SPL vs. IOP – All Subjects

Sound Envelope

The data collected from Task A provide a sense of the physical framework in which the oboe operates. This sound envelope describes the upper and lower boundaries of air pressure required to produce sound on the instrument, for the range of possible sound pressures. For the oboe, these boundaries are based on the acoustic properties of the instrument and reed (maximum airflow through the bore, resistance, impedance, admittance), and the human operator's ability to produce a stable air column while manipulating the reed to alter its vibration profile.[1]

Figure 22 shows the sound envelope for the oboe, derived from the crescendo-decrescendo data from Task A. All four pitches studied (D4, G4, C5, and A5) and all subjects' measurements are included in this scatter plot. The plot is bounded by reference lines on both axes at a lower percentile of 2.5 and an upper percentile of 97.5; the central region within these lines contains 95% of the data points from Task A.

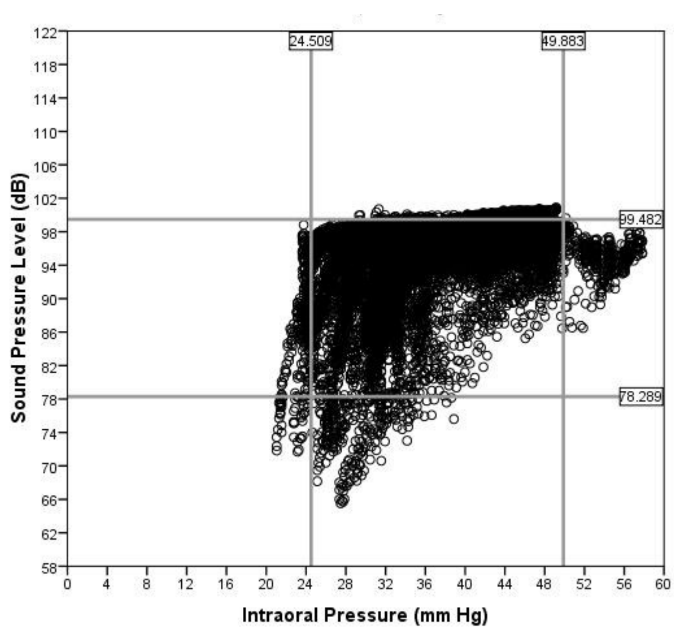


Figure 22. Sound Envelope of the Oboe

[1] For an excellent treatment of this subject, the reader is referred to Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments*, 2d ed. (New York: Springer-Verlag, 1998), chap. 13, 15.

The central bounded region of figure 22 represents the physical profile of the oboe: it shows the range of possible sound pressures that can be produced, and how much air pressure is required to do so. This is not a complete profile, as only four pitches were studied. However, the range from D4-A5 represents the majority of the oboe's functional register, omitting only the very lowest and highest notes.

Under the conditions of Task A, where performers were attempting to play through their entire range of possible dynamics, the oboe functions between approximately 25 and 50 mm Hg, yielding a sound pressure between approximately 78 and 100 decibels (dB). For the subjects studied, the lowest recorded IOP was 21.043 mm Hg (for the pitch C5), but the lower limit of the 95% confidence envelope was 24.509 mm Hg; this appears to be the minimum air pressure required to sustain vibration of the oboe reed at that pitch level. Figure 22 also shows a general trend of lower IOP yielding lower SPL, and higher IOP yielding higher SPL. Only higher sound pressures (above 85 dB) were measured when IOP was high, but at low IOP levels (near 25 mm Hg) the full range of SPL measurements was still detected.

Table 15 reports the minimum, maximum and percentile values used to characterize the oboe's sound envelope. This data indicates that there is a linear relationship between SPL and IOP for the lower portion of the oboe's dynamic range, but for the higher dynamic range the relationship becomes nonlinear: in this range, further increases of IOP yield only minimal increases in SPL. Previous research has shown a wide variation in maximum expiratory pressures among humans in different test conditions, as discussed in chapter 2; however, regardless of a particular player's capacity to generate air pressure, the instrument itself has a limit that, if exceeded, does not result in a change in the performance result (SPL). For example, Fletcher and Tarnopolsky demonstrated that for a large part of the dynamic range of the trumpet, each doubling of blowing pressure gives a 15 dB increase in sound output, but when nearing the upper threshold of a given note, each further doubling of blowing pressure yields only a 3 dB increase. For the trumpet, then, players can increase their blowing pressure beyond what is necessary for a given condition but gain only a minimal increase in SPL.[2]

Table 15. Min/Max Values from Task A – All Subjects

Pitch	Minimum Recorded	2.5th Percentile	Median	97.5th Percentile	Maximum Recorded
			Intraoral Pressure (mm Hg)		
D4	23.642	24.137	33.049	44.932	45.551
G4	22.776	24.508	34.040	47.532	48.274
C5	21.043	23.765	33.668	48.521	51.863
A5	24.632	27.975	40.723	55.701	57.805
All	21.043	24.509	34.411	49.883	57.805
			Sound Pressure (dB)		
D4	76.217	87.002	97.598	99.011	99.529
G4	71.695	80.780	96.232	99.482	100.140
C5	68.163	75.981	94.301	98.352	99.670
A5	65.526	76.028	96.986	100.381	100.890
All	65.526	78.289	96.374	99.482	100.890

The data shown in table 15 do not completely confirm the findings of Fuks and Sundberg, who reported that low notes on the oboe require more air pressure than higher notes when playing softly, and suggested that the embouchure is more important

[2] Neville H. Fletcher and A. Tarnopolsky, "Blowing Pressure, Power, and Spectrum in Trumpet Playing," *Journal of the Acoustical Society of America* 105, no. 2, pt. 1 (1999): 880.

than IOP for regulating loudness.[3] As seen in table 15, in this study D4 did require more IOP than G4 or C5, but D4 was also played louder than G4 or C5.

Figure 23 shows the 95% envelope boundaries for each individual pitch of the study. These four plots show that, as pitch rises, the amount of IOP required to produce that pitch gradually increases both for soft and loud dynamics. However, the maximum SPL produced for each pitch does not change substantially between low and high pitches. D4 and G4 have very similar profiles; C5 begins to show an increase in IOP, and A5 shows a noticeable IOP increase as well as a slight increase in maximum SPL. None of these increases are very large, a few mm Hg or dB at most.

These plots also show the nonlinearity of the sound envelope at higher levels of IOP – each plot shows a clear knee-shaped bend where the linear growth phase ends and the nonlinear phase begins; the plot for C5 (figure 23C) shows the most obvious transition between the two phases. Beyond observing this trend, calculating the actual point of nonlinearity is beyond the scope of this study.[4]

The pedagogical implication of this data is that oboists should avoid blowing excessively hard to produce a given pitch, instead doing just enough work to place the note exactly where it needs to be, particularly when executing an upward leap. This will decrease fatigue and increase endurance. The player may perceive an increase in support of the air column that feels very large, but the actual air pressure requirements for low and high notes are not drastically different (compare the boundaries of figures 23A and 23D, for example).

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[3] Leonardo Fuks and Johan Sundberg, "Blowing Pressures in Bassoon, Clarinet, Oboe and Saxophone," *Acta Acustica united with Acustica* 85, no. 2 (1999): 270.

[4] The subject of nonlinearity in wind instruments is covered in detail in Neville H. Fletcher, "Air Flow and Sound Generation in Musical Wind Instruments," *Annual Review of Fluid Mechanics* 11 (1979): 123-46.

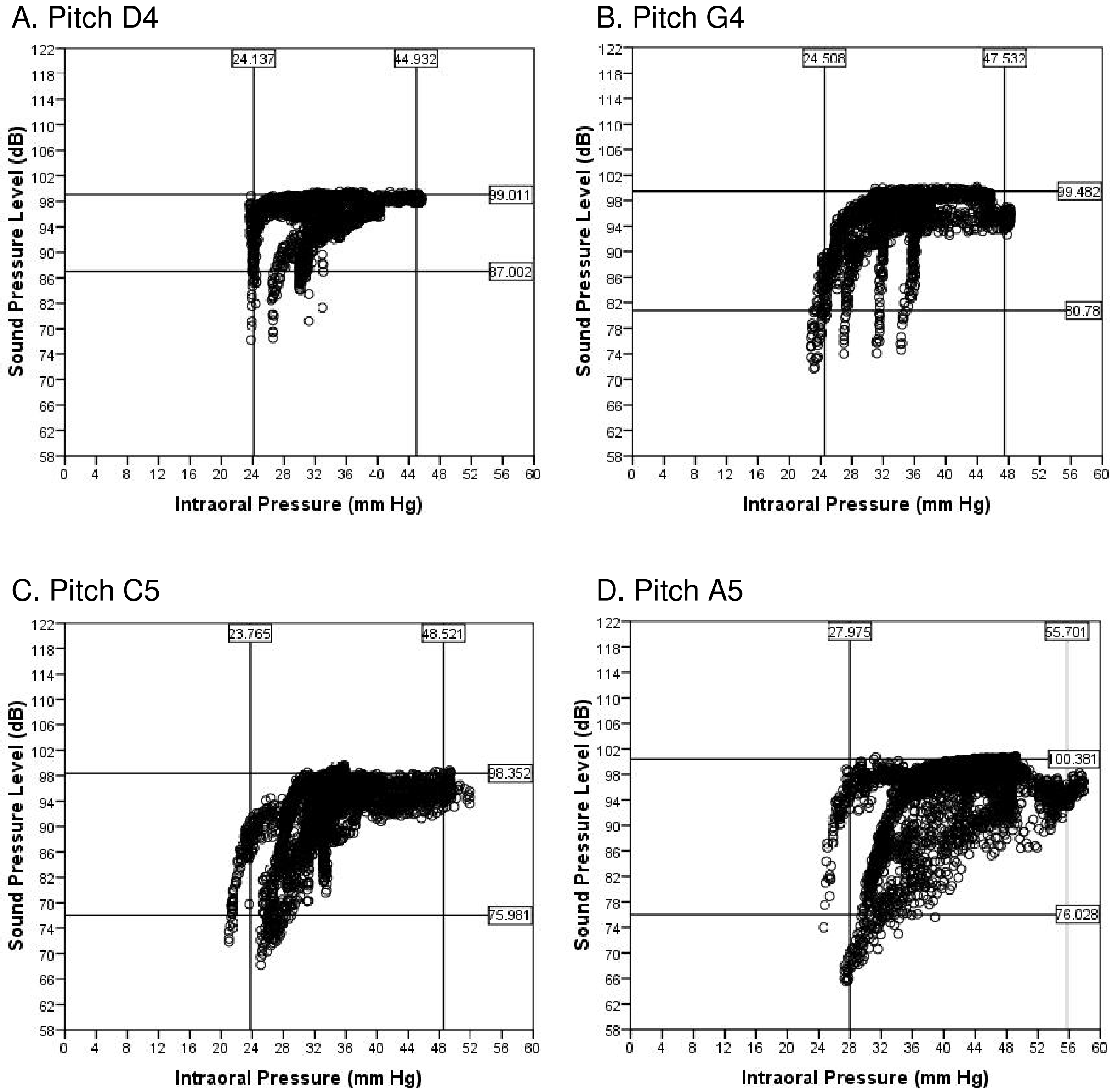

Figure 23. Sound Envelope of Individual Pitches – All Subjects

Oboists should acknowledge the sensation of working harder, but not translate that directly into action such as trying to double air pressure when playing an ascending octave leap. This is a good example of how exposure to research data or the opportunity to gather such measurements directly could aid the musician in making informed decisions about how to play, to bridge the gap (discussed in chapter 1) between perception and reality in performance.

Finally, there is a very clear upper limit of possible sound pressure between 98 and 102 dB across all recorded intraoral pressures, while the lower SPL limit is much more variable. The upper limit is strictly constrained by the physical properties of the instrument and reed, while the lower limit depends (in addition to the same physical properties) on the performer's ability to manipulate the reed with their embouchure and air column to produce the softest possible tone.

Tables 16 and 17 summarize the minimum and maximum IOP and SPL measurements for all subjects, highlighting the variability among individuals in their ability to play softly. The greater variability of the minimum SPL compared to the maximum is clear from table 17: at maximum, the means are very similar across all pitches, and the ranges and standard deviations are very small. In contrast, the means for minimum SPL have a greater spread, and their ranges and standard deviations are much higher.

The picture is different for intraoral pressure (table 16), where the minimum and maximum values for each pitch have a much greater range and standard deviation, and the values for range and SD are more similar between minimum and maximum levels. To further clarify the example of performers blowing harder than necessary, the per-subject maximum IOP values for each pitch studied vary widely (Table 16; SD between 3.453 and 7.065 mm Hg), but the corresponding SPL outputs for the same pitches show little variation (table 17; SD between 0.491 and 0.902 dB).

Table 16. Min/Max IOP (mm Hg) by Pitch and Subject

Subject ID:

	1	2	3A	3B	4A	4B	$\bar{x}$	(SD)	Range
	Minimum IOP								
D4	26.365	23.642	30.574	32.678	23.766	24.384	26.901	(3.845)	9.036
G4	26.984	22.776	30.697	34.039	23.147	N/A	27.529	(4.861)	11.263
C5	25.993	21.043	31.069	33.049	25.375	25.128	26.943	(4.377)	12.006
A5	27.355	24.632	34.534	35.895	29.336	29.707	30.243	(4.273)	11.263
	Maximum IOP								
D4	40.352	45.551	37.010	36.391	34.534	34.782	38.103	(4.205)	11.017
G4	45.674	48.274	33.420	36.762	38.124	N/A	40.451	(6.264)	14.854
C5	49.388	51.863	35.153	40.847	38.495	35.896	41.940	(7.065)	16.71
A5	57.805	50.130	49.140	49.017	50.502	48.769	50.894	(3.453)	9.036

Table 17. Min/Max SPL (dB) by Pitch and Subject

Subject ID:

	1	2	3A	3B	4A	4B	$\bar{x}$	(SD)	Range
	Minimum SPL								
D4	76.499	88.273	79.184	81.303	76.217	81.915	80.565	(4.453)	12.056
G4	74.003	73.438	74.097	74.662	71.695	N/A	73.579	(1.139)	2.967
C5	70.377	71.837	78.195	79.560	76.217	68.163	74.058	(4.589)	11.397
A5	65.526	74.003	90.958	80.173	74.192	74.286	76.523	(8.478)	25.432
	Maximum SPL								
D4	98.305	99.529	99.435	99.529	98.917	99.435	99.192	(0.491)	1.224
G4	100.140	97.786	98.776	99.058	99.717	N/A	99.095	(0.908)	2.354
C5	98.823	98.257	97.881	99.482	98.446	99.670	98.760	(0.704)	1.789
A5	98.681	100.710	100.890	99.482	99.199	99.152	99.686	(0.902)	2.209

Clearly the test subjects are using different amounts of physical effort but all are delivering a similar level of sound output for any given pitch. Some of these variations may be due to physical properties of the subjects' reeds and instruments, but it is also likely that a study of the minimum air pressure needed to produce a given pitch would be of value to the performer. Figure 24 plots the minimum and maximum values from Task A for each subject to show the variance among performers graphically.

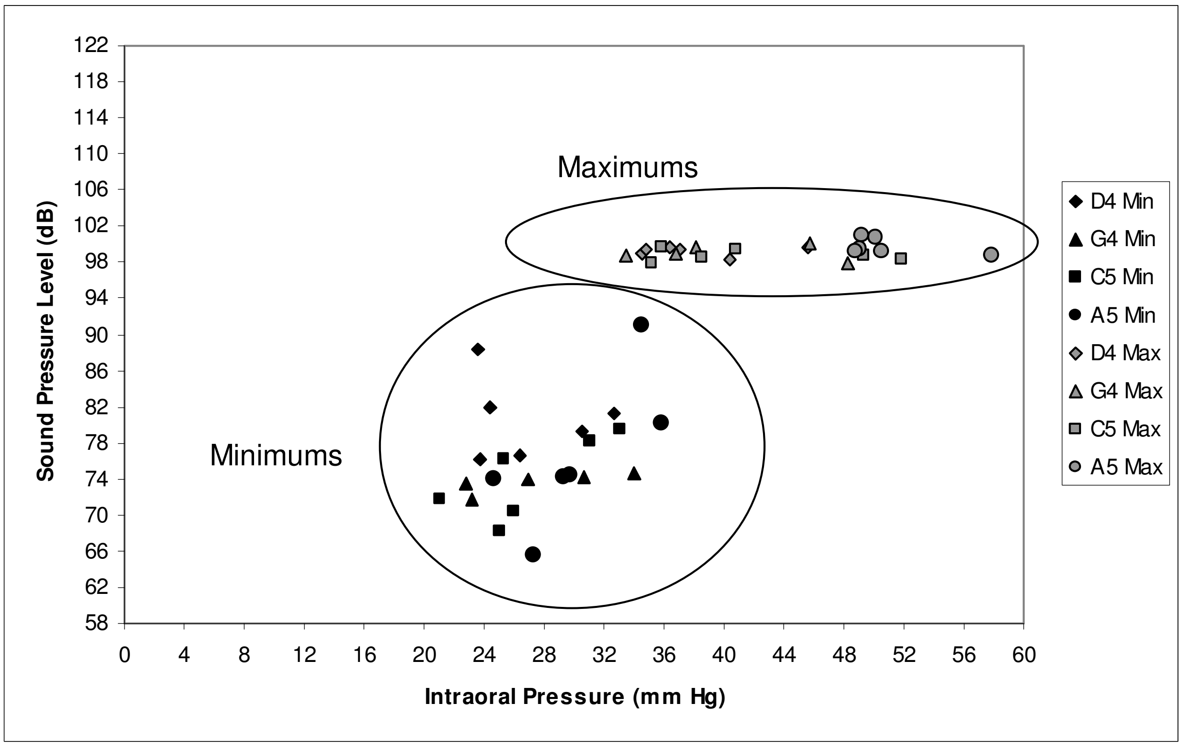

Figure 24. Min/Max Data Points – SPL vs. IOP – for All Subjects

The oboe is limited both by its small range compared to the other woodwind instruments (Bb3-F6 in most situations, with an infrequently called-upon altissimo range up to C7 for skilled players) and by its restricted profile of dynamic flexibility, as illustrated by the data shown above. Perhaps this explains in part why oboe pedagogy places a high priority on reed making and development of tone quality, to maximize the potential of the small set of tools available to the oboist.

A Laryngoscopic View of Dynamic Contrast

The dynamic ranges of the various notes studied during this project have been described above. The laryngoscopic images collected during Task A indicate that the glottis plays a role in the regulation of air pressure during the course of a crescendo or decrescendo. Figures 25 and 26 show nasoendoscopic (FFN) images from Task A for two subjects: 1 (superior position), and 4B (inferior position).

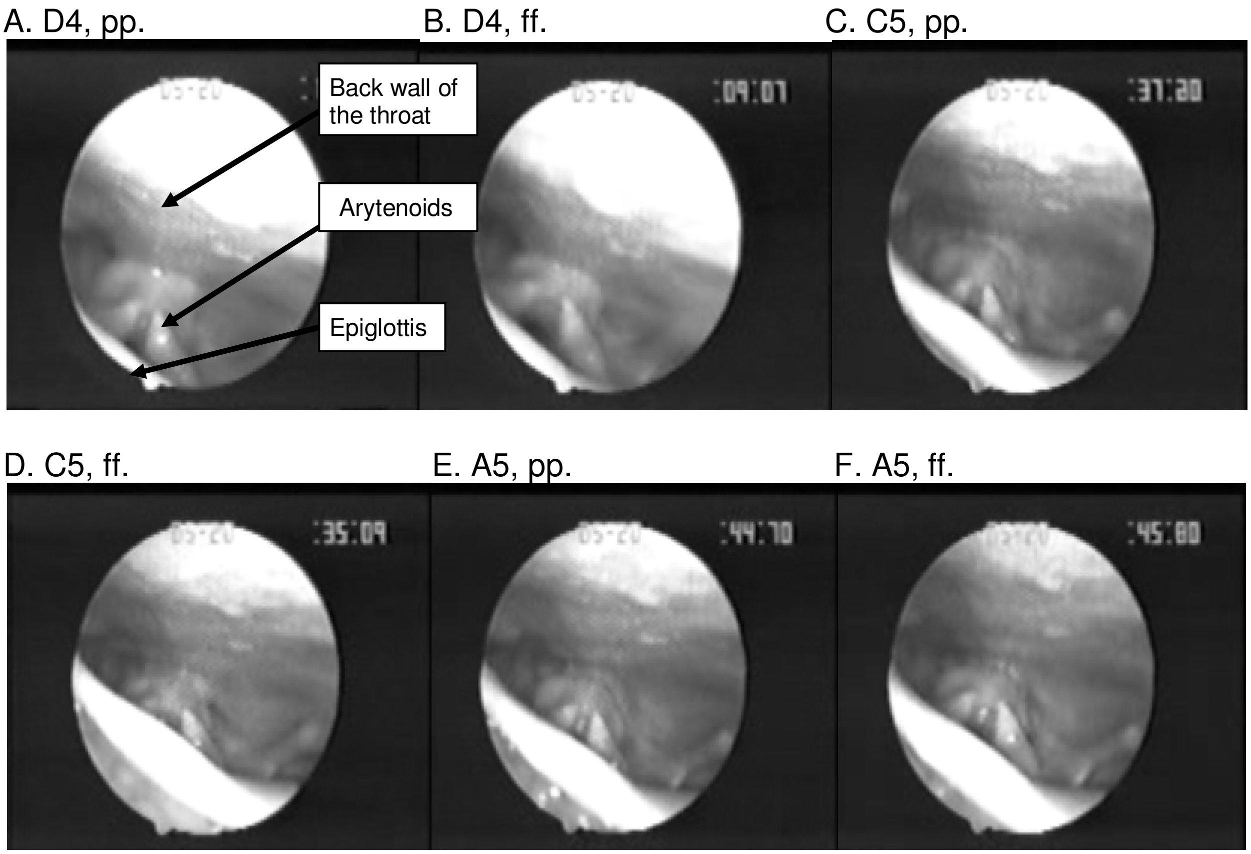

Figure 25. Subject 1 – FFN Images During Crescendo

The 6 images for Subject 1 (figure 25) are partially obscured by the base of the tongue, which moves towards the back of the throat when tone is being produced. However, it is possible to see the position of the arytenoid cartilages which can be correlated to the aperture of the vocal folds. Each pair of images (25A-B, 25C-D, and 25E-F) shows the same pitch being played at opposite dynamic extremes, first *pp* then *ff*. In each case, the arytenoids are more closed at the softer dynamic, and more open at the louder dynamic.

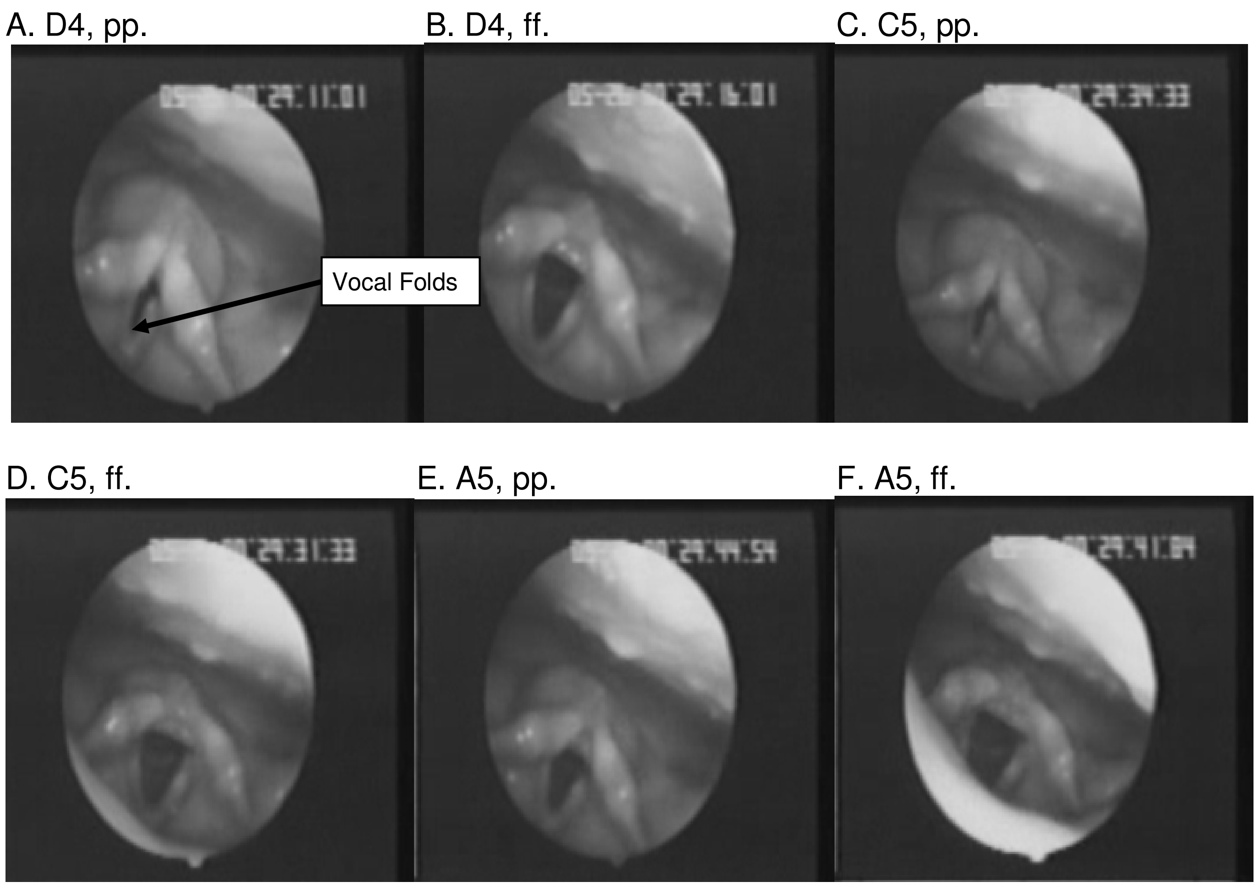

Figure 26. Subject 4B – FFN Images During Crescendo

The three pairs of images from Subject 4B (figure 26) are much clearer as the camera was in an inferior position. Again, the aperture of the vocal folds is small when playing *pp* and large during *ff*. King et al. have also observed that the vocal folds appear to be involved in air pressure regulation in the woodwinds;[5] further research is warranted, as the images shown here are not graduated and so no detailed conclusions can be drawn.

Vibrato

Vibrato can be a controversial topic among woodwind instrumentalists. There are many different opinions on how it is produced and controlled, and much disagreement about how to teach it. Many visual studies of laryngeal function have shown that the structures of the larynx and pharynx participate, either actively or passively, in the propagation of vibrato. For example, King et al. found via FFN that the vocal folds oscillate during vibrato on all woodwind instruments, while Rydell et al. observed vocal fold motion on the flute but not on the saxophone or trumpet (not surprising given that vibrato on these instruments is typically produced with the lip and/or the jaw).[6] Using videofluorography, Carr observed that double reed musicians move their tongues down and open their throat during vibrato, and Kahane et al. discovered both vocal fold and soft palate motion during vibrato on the bassoon.[7] Martin Schuring, a respected oboe

[5] Austin I. King, Jon Ashby, and Charles Nelson, "Laryngeal Function in Wind Instrumentalists: The Woodwinds," *Journal of Voice* 1, no. 4 (1988): 366.

[6] King et al., "The Woodwinds," 366-67; Roland Rydell et al., "Laryngeal Activity During Wind Instrument Playing: Video Endoscopic Documentation," *Logopedics, Phoniatrics, Vocology* 21 (1996): 44-45.

[7] Walter Edward Carr, Jr., "A Videofluorographic Investigation of Tongue and Throat Positions in Playing Flute, Oboe, Clarinet, Bassoon, and Saxophone" (DMA diss., University of Southern California, 1978), 79; J. C. Kahane et al., "Videofluoroscopic and Laryngoscopic Evaluation of the Upper Airway and Larynx of Professional Bassoon Players," *Journal of Voice* 20, no. 2 (2006): 300, 302-3.

pedagogue, teaches that all vibrato, regardless of the player's perception, is centered on the larynx.[8]

Accepted pedagogy for American oboe vibrato suggests that it should be a push on the airstream and a return to the starting point, rather than a complete upward and downward bend of the pitch (as observed on string instruments, for example).[9] Accordingly, allowing the air pressure to dip too far below the starting point or allowing the vibrato to have too wide of an amplitude would cause the intonation to go flat, and should be avoided. If this hypothesis about vibrato production is correct, the new, wider IOP range of a vibrated pitch should be slightly biased above the mean for the same straight pitch, indicating that the performer is pushing the air column and then allowing it to relax, but controlling that relaxation so that air pressure does not sink too far.

Each test subject from this study employed a different style of vibrato. Subject 3 showed only minimal vibrato, with a small change in IOP and SPL throughout. Subjects 1 and 4 had a moderate vibrato, with Subject 1 having greater evenness and control than 4. Subject 2 had a wider vibrato with faster amplitude and more audible alteration of the pitch than the other subjects. For all subjects the addition of vibrato to a stable pitch produced an increase in the range of IOP and SPL values for that note – refer to figures 11-18 and tables 6-13 in chapter 4 to see the difference between straight tones and vibrated tones. To illustrate the effect of vibrato on the oboe tone, figure 27 shows a set of frequency distributions of the IOP and SPL data for Subject 1's straight and vibrated performances of pitch D4.

[8] Martin Schuring, *Oboe Art & Method* (New York: Oxford University Press, 2009), 24.

[9] Robert Sprenkle and David Ledet, *The Art of Oboe Playing* (Miami: Summy-Birchard Music, 1961), 25-26.

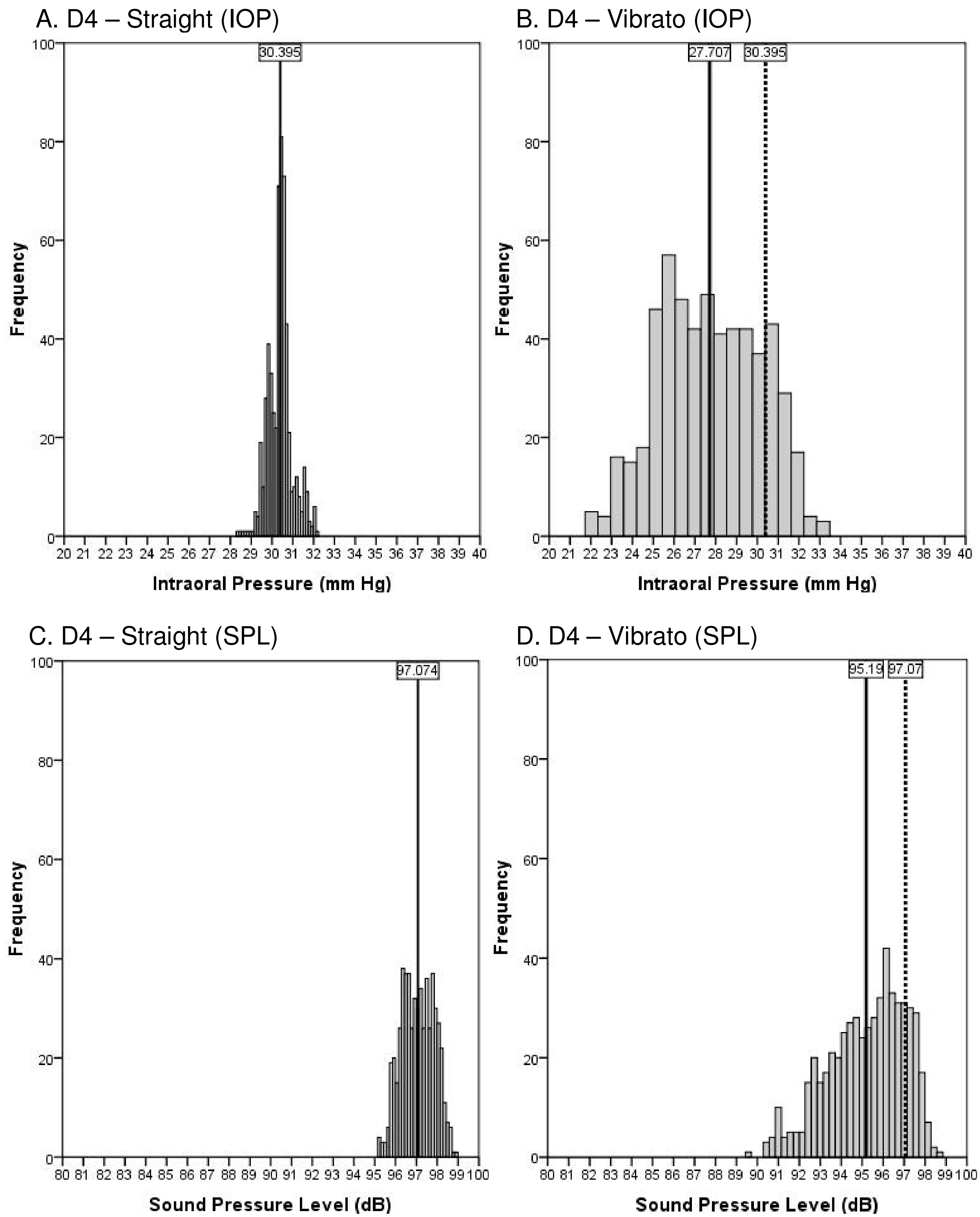

Figure 27. Pitch D4 – Subject 1 – Straight vs. Vibrato Tone

For the straight-tone charts (figures 27A and 27C), the reference line is for the mean. For the vibrato-tone charts (figures 27B and 27D), the solid reference line is for the new vibrato-tone mean and the dashed line is for the original straight-tone mean. As can be seen from this figure, the new IOP and SPL ranges for this subject's vibrato performance are both wider than for the equivalent straight-tone performance, and both are also heavily biased below the straight-tone means for the same pitch.

This subject's results are shown as scatter plots in figure 28. In figure 28A, the reference lines are for the straight-tone mean; in figure 28B, the solid lines are for the vibrato-tone mean while the dashed lines show the original straight-tone mean. Both the wider dispersion of the vibrato performance and its bias below the original mean are visible in figure 28B.

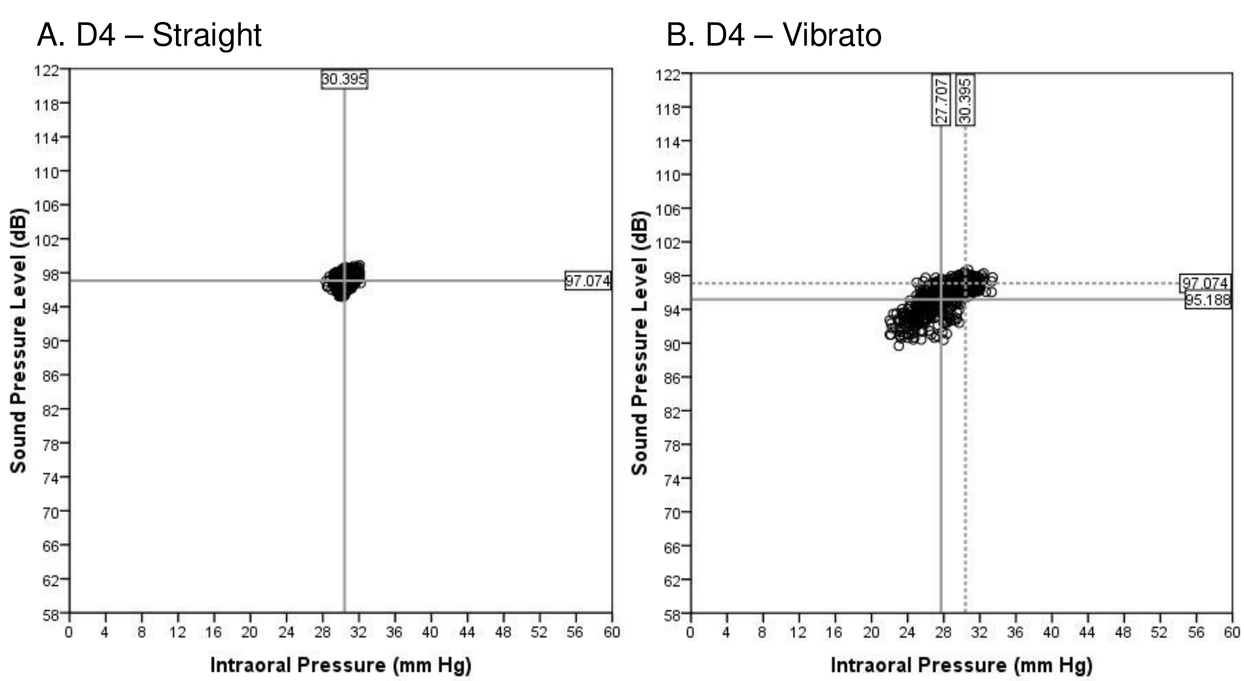

Figure 28. Pitch D4 – Subject 1 – Comparison of Means and Dispersion

The following figures (29-32) show IOP and SPL data from a two-second sample of each vibrato pitch. Subjects 3A and 3B were very similar, as were 4A and 4B; therefore, the following set of illustrations omits Subjects 3B and 4A. Each graph also includes a reference line for the straight-tone mean IOP from that subject and pitch.

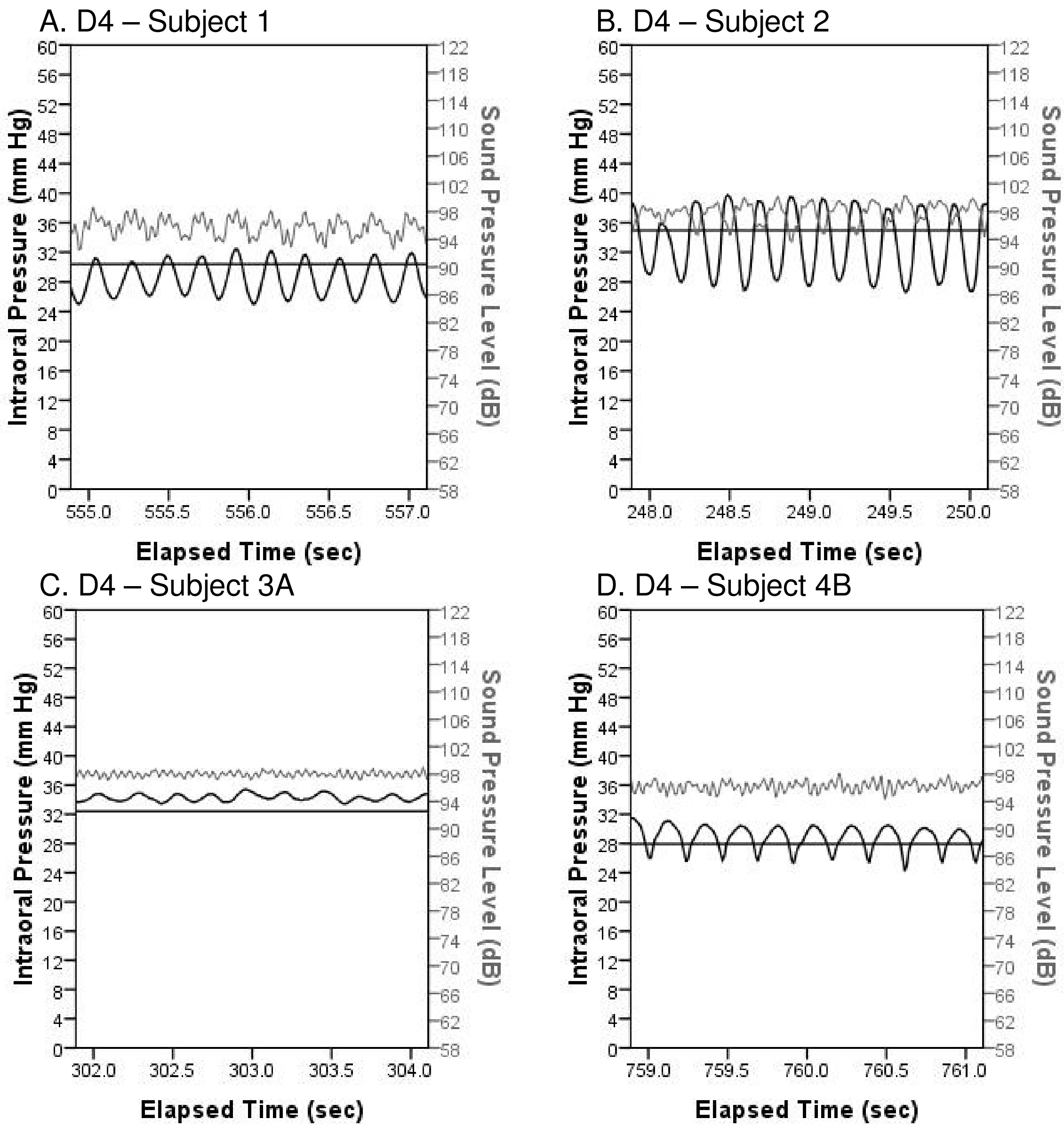

Figure 29. Pitch D4 – Vibrato Samples

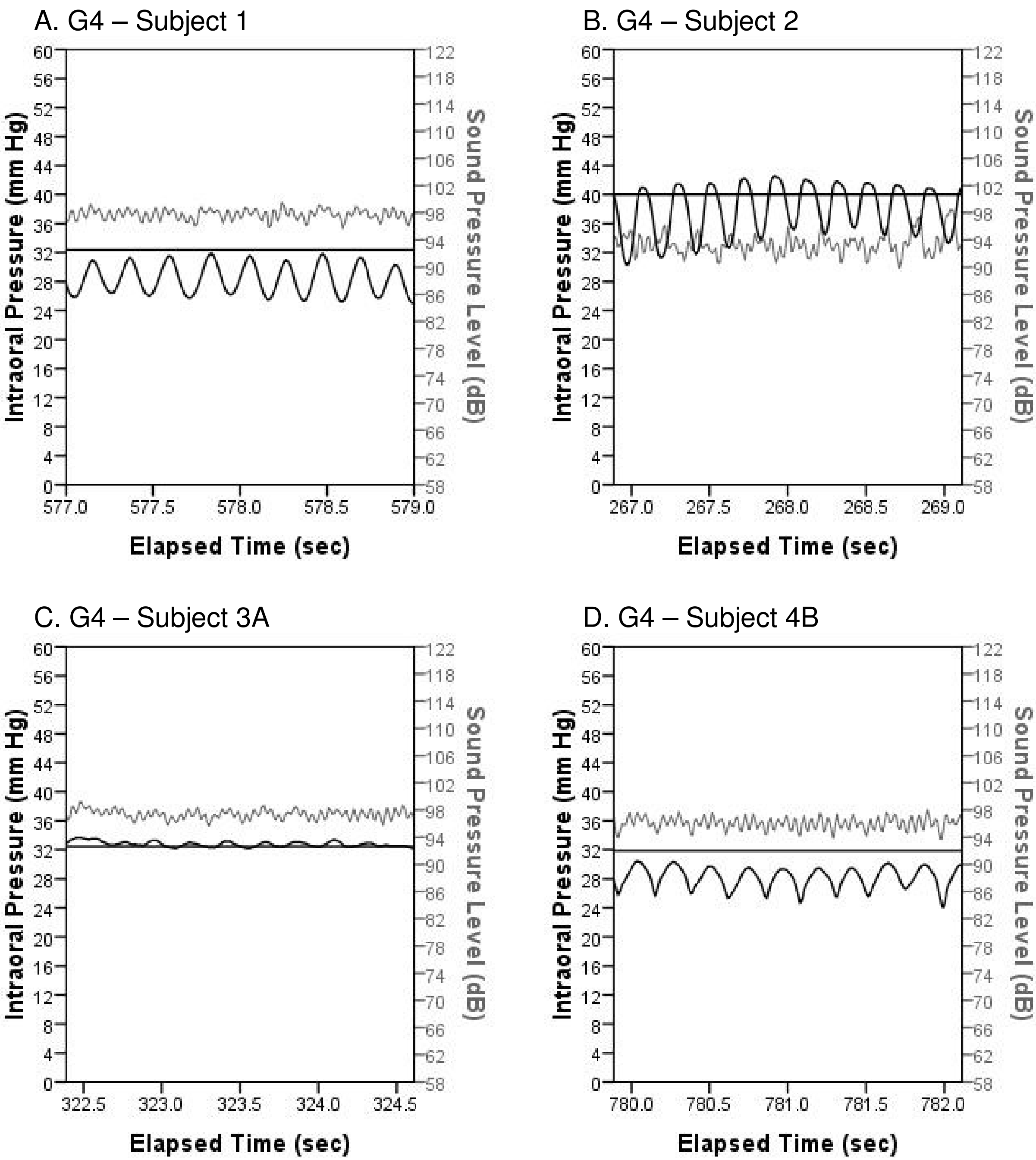

Figure 30. Pitch G4 – Vibrato Samples

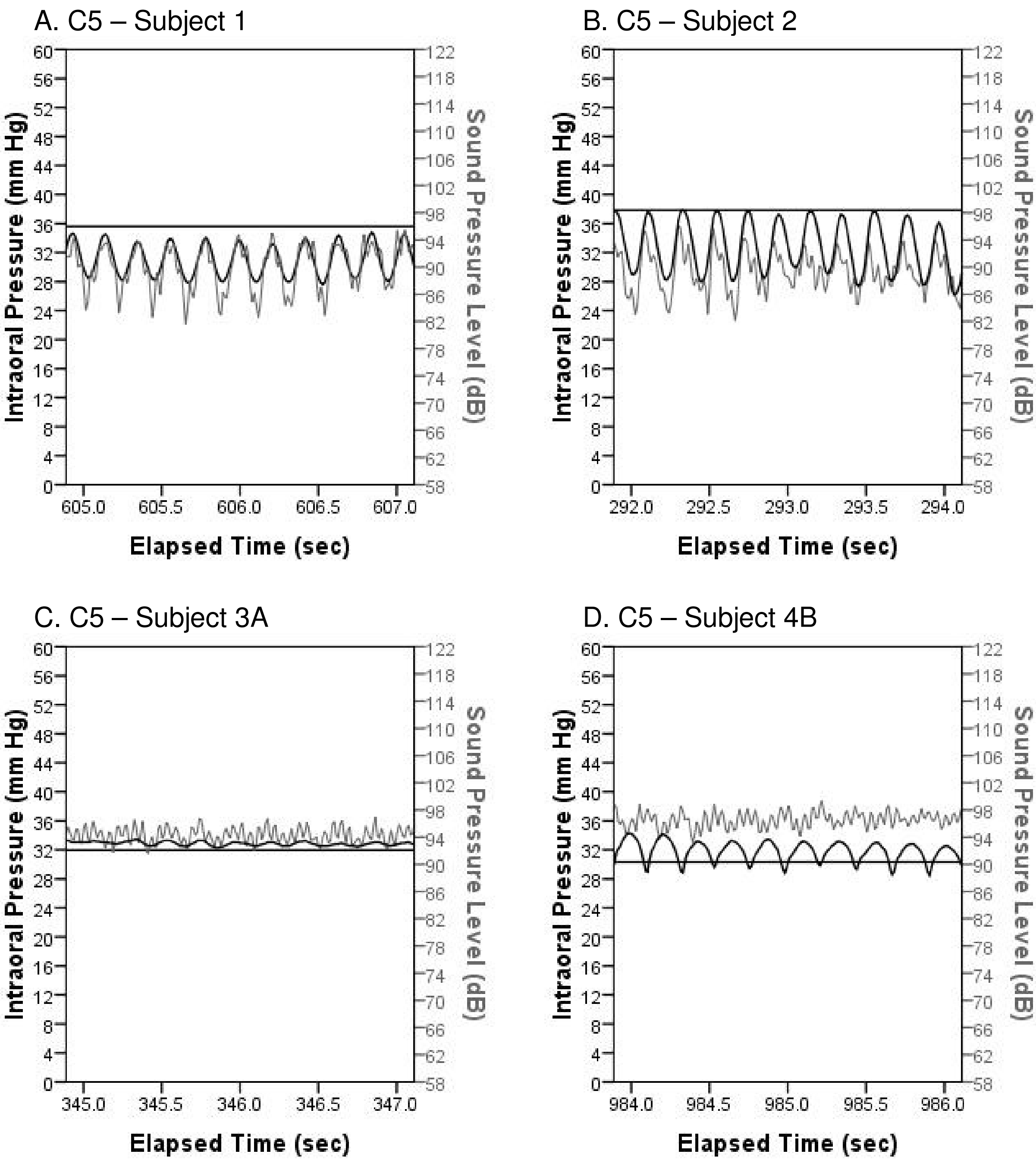

Figure 31. Pitch C5 – Vibrato Samples

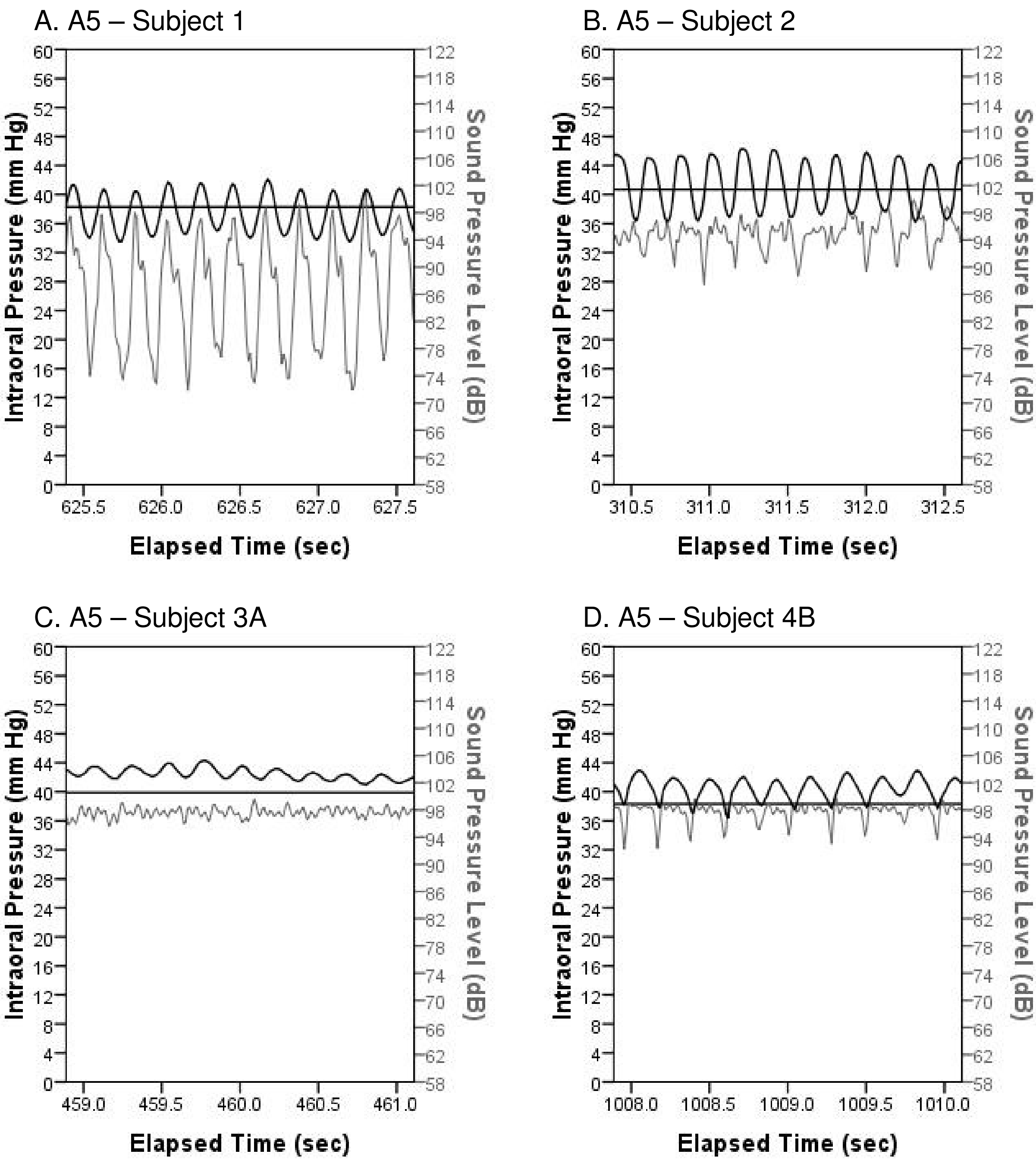

Figure 32. Pitch A5 – Vibrato Samples

Based on these two-second samples extracted from each vibrato performance, Subject 3 is the only player who consistently had a vibrato that was set above their mean for straight-tone IOP. Of the remaining performers, Subjects 1 and 2 showed vibrato air pressures that were consistently below their straight-tone means, except for the pitch A5 when both subjects stayed relatively centered on their means. Subject 4 showed the greatest variation in placement of vibrato IOP relative to the straight-tone mean: centered for pitch D4, below for pitches G4 and C5, and above for pitch A5. In general, all subjects vibrated above their straight means while playing A5. This study lacks sufficient evidence to draw a conclusion about quality of tone and the placement of vibrato, but the previously-stated hypothesis about how vibrato should be manipulated certainly is not definitively supported here, and needs further investigation.

Considering the vibrato task as a whole, Subject 2 had the widest IOP and SPL amplitude during vibrato (apart from Subject 1's SPL amplitude for pitch A5, which was the largest observed amplitude), and this subject's IOP tended to drift or sag noticeably over the course of a typical performance. Subject 3 had the smallest amplitudes and the smallest centerline drift during any pitch; this subject's vibrato was difficult to detect in the audio recording of the test session. Subjects 1 and 4 showed a medium level of IOP and SPL amplitude, and their performances showed low to medium amounts of IOP centerline drift (compare figures 16A-F from chapter 4 to see these differences clearly). An evaluation of the recordings for all subjects revealed that Subjects 1 and 4 demonstrated the greatest control over their tone quality and stability of intonation during vibrato.

The frequency of the vibrato pulse, observed qualitatively from the IOP wave, was between 4-5 cycles per second (Hz) for all subjects. Subjects 1 and 2 had the fastest frequencies (close to 5 Hz) and Subjects 3 and 4 had the slowest (close to 4

Hz); in a 1998 study, Fuks reported vibrato frequencies between 4.5 and 6.5 Hz among all woodwind instruments, with a corresponding SPL amplitude modulation of ±1.0 dB at a *mf* dynamic, and ±1.3 dB at a *ff* dynamic.[10] The vibrato amplitude modulations from the current study are shown in table 18 (calculated from the range data from tables 7, 9, 11, and 13), reported as the mean of all subjects for each pitch as well as the mean of all pitches together. While the all-subject IOP means for each pitch are very similar, they produced dissimilar responses in the all-subject SPL means. It appears that the higher notes are less stable and more easily perturbed by small changes in air pressure.

Table 18. Vibrato Amplitude Modulation

Pitch	Straight Tone	Vibrato Tone
IOP (± mm Hg)		
D4	1.743	4.343
G4	2.177	4.559
C5	2.280	4.363
A5	1.816	4.312
Mean	2.004	4.394
SPL (± dB)		
D4	1.566	2.740
G4	2.473	3.831
C5	4.192	6.935
A5	4.078	6.260
Mean	3.077	4.941

A final point about vibrato needs to be addressed. Careful study of the vibrato samples presented in figures 29-32 shows that, while most subjects show the expected

[10] Leonardo Fuks, “Aerodynamic Input Parameters and Sounding Properties in Naturally Blown Reed Woodwinds,” *Speech, Music and Hearing: Quarterly Progress and Status Report* 4 (1998): 5-6.

result of increased IOP yielding increased SPL and vice versa, this is not always true. In particular, pitch D4, Subject 2 (figure 29B), D4-3A (29C), G4-2 (30B) and C5-4B (31D), the SPL curve actually decreases when the IOP curve goes up, as if the two wave forms were in opposition. This is also visible for A5-2 (32B) and A5-3A (32C); in these two cases the typical form is observed at first and then SPL and IOP waves move into opposition part way through the excerpt. Figure 33 shows that Subject 1 has a positive linear regression for SPL vs. IOP (the expected outcome), while Subject 4B has a negative linear regression (SPL decreases as IOP increases).

A. Subject 1 B. Subject 4B

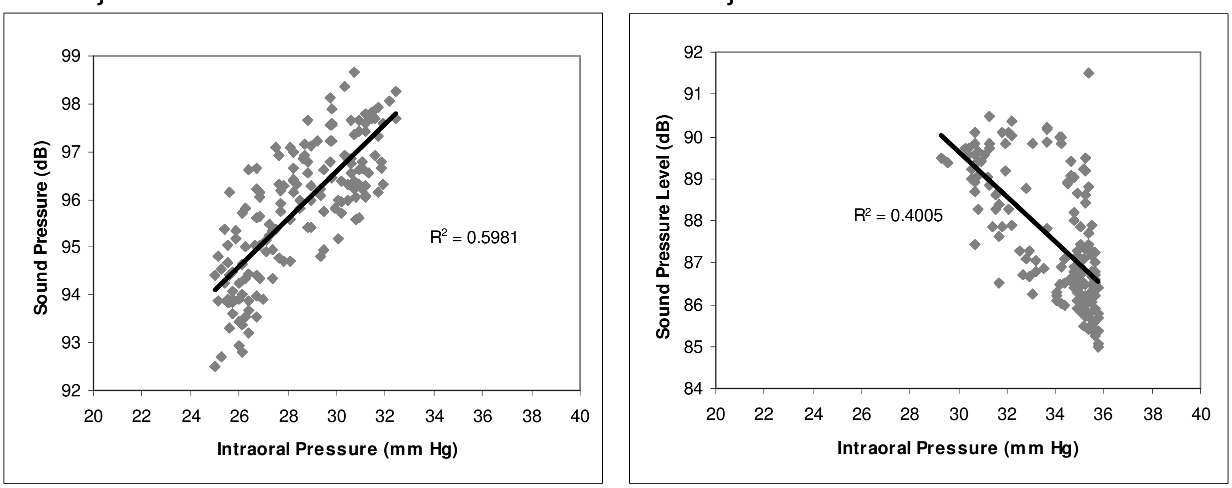

Figure 33. Pitch C5 (Vibrato) – Subject 1 vs. 4B

This cannot be adequately explained with the data available. The laryngoscopic images for Subject 1 show a unified, mild, stable oscillation of the glottis, the walls of the throat and the tongue during vibrato, while Subject 4B shows an alternation between pulsation of the glottis and ventral-to-dorsal motion of the tongue with little or no motion of the throat itself; simply a few oscillations of the glottis, followed by a few motions of the tongue, but never the two moving together.

A series of these images from the vibrato performance of pitch C5 (0.1 seconds apart) are shown in figures 34 (Subject 1) and 35 (Subject 4B) for comparison. The images for Subject 1 show little obvious variation when viewed in still form – the vocal tract motions are unified and small. Subject 4B's images, however, clearly show the two-phase technique this subject uses to produce vibrato. In figures 35F through 35L the transition between glottal motion and tongue motion is particularly clear. Perhaps the type of vibrato production is a factor in the unusual scenario (described above) where sound pressure and intraoral pressure are inversely related. Additionally, in the case of Subject 4B, the IOP wave form during vibrato (for example, see figure 29D) is not evenly shaped – there is a rounded bulge at the peak of each cycle followed by a sharp trough. The other subjects, particularly 1 and 2, show a smoother, sinusoidal IOP wave (see figures 29A and B).

This needs further investigation as the laryngoscope shows vocal tract motion but does not distinguish between motion that is generating the vibrato pulse, and sympathetic motion in response to a vibrato pulse produced elsewhere in the airway. Experience may also be a factor; Subject 1, who did not display this inverse phenomenon, had the most playing experience (18 years; the other subjects had no more than 11 years of experience). However, Subject 3 and Subject 4 both had 11 years of experience, and Subject 3 tended not to have this issue while Subject 4 did.

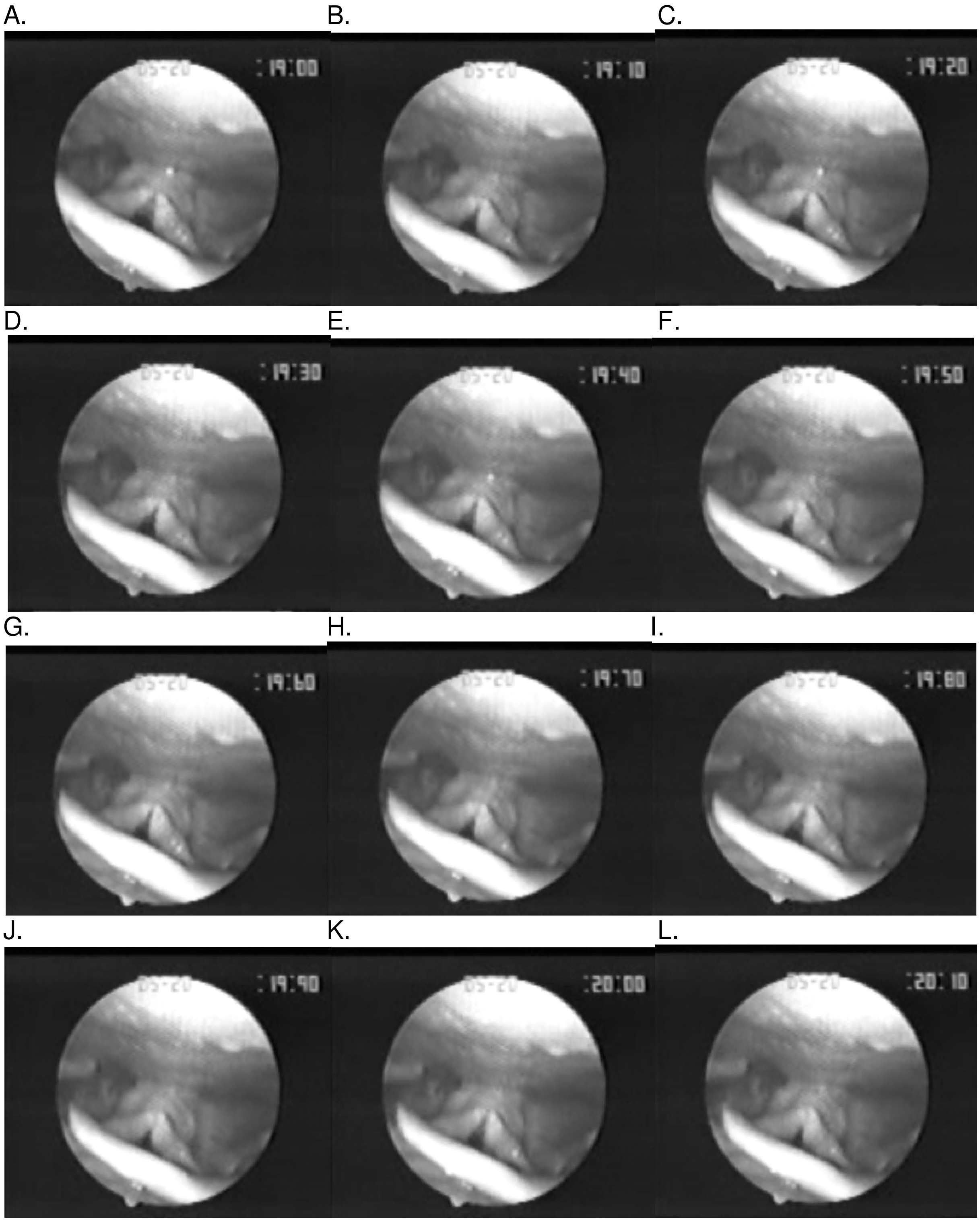

Figure 34. Subject 1 – FFN Images During Vibrato – Pitch C5

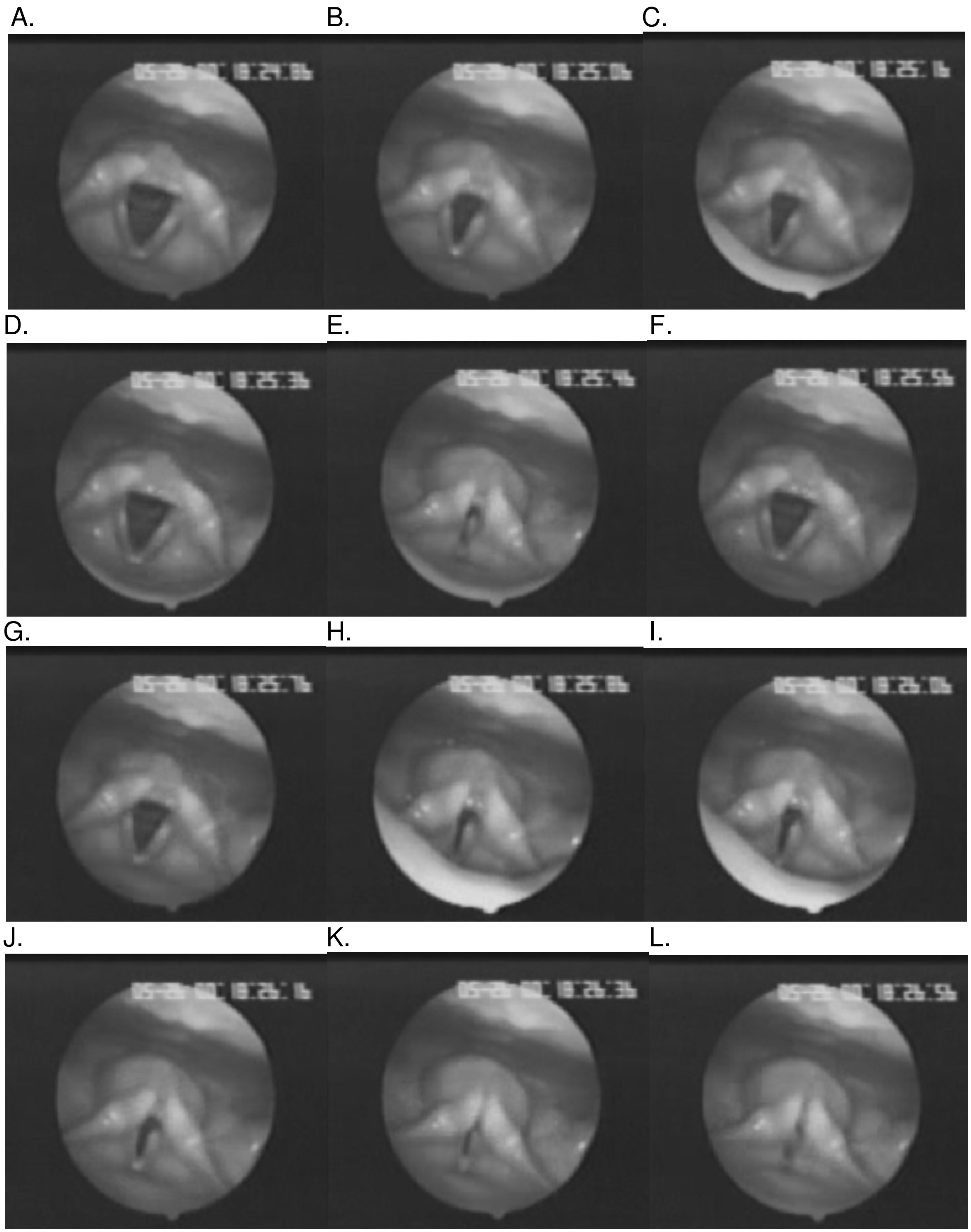

Figure 35. Subject 4B – FFN Images During Vibrato – Pitch C5

The Role of Experience

An individual's level of training and experience is an important factor along with natural ability in determining the quality of their tone and technique on any instrument. It is commonly known that young oboists, particularly those in junior high school (grades 6-8) tend to lag behind their colleagues who have the same amount of training but play other instruments. An important aspect of tone control is the ability to shape the start and end of a note; another is the player's ability to produce a stable tone that does not fluctuate in timbre, intonation or loudness. This second type of long-tone exercise (simulated by the straight-tone portion of Task B) is a commonly used training task both for beginners and professionals. This study did not have enough participants to allow generalization about experience, but two observations can nevertheless be drawn from a comparison between Subject 1, with 18 years of experience as an oboe player, and Subject 2, with 9 years of experience. These two subjects were of a similar age: Subject 1 was 29 years old and Subject 2 was 27 at the time of this study.

An examination of the Task B figures from chapter 3 associated with Subjects 1 and 2 (figure 11A vs. 11B, figure 12A vs. 12B, and so forth), suggests that Subject 1 was able to create a quicker, more stable taper at the end of a note than Subject 2. In general, Subject 1's IOP drops smoothly and quickly at the very end of tone production, while Subject 2's air pressure starts to drop early, well in advance of the actual end of the note. This translates to a slight sag in intonation at the end of the note.

Figures 36 and 37 compare straight-tone scatter plots from Task B for both subjects. In each case, the plot for Subject 1 shows a tighter dispersion of data points than does the corresponding plot for Subject 2. Both subjects placed each note in the same general location in terms of the air and sound pressures for *mf* playing; only the stability of the note was different between subjects. While many factors contribute to tone control, most importantly the reed itself, the players' training will equip them to control the response of the reed as they wish, to the limit of their physical skill.

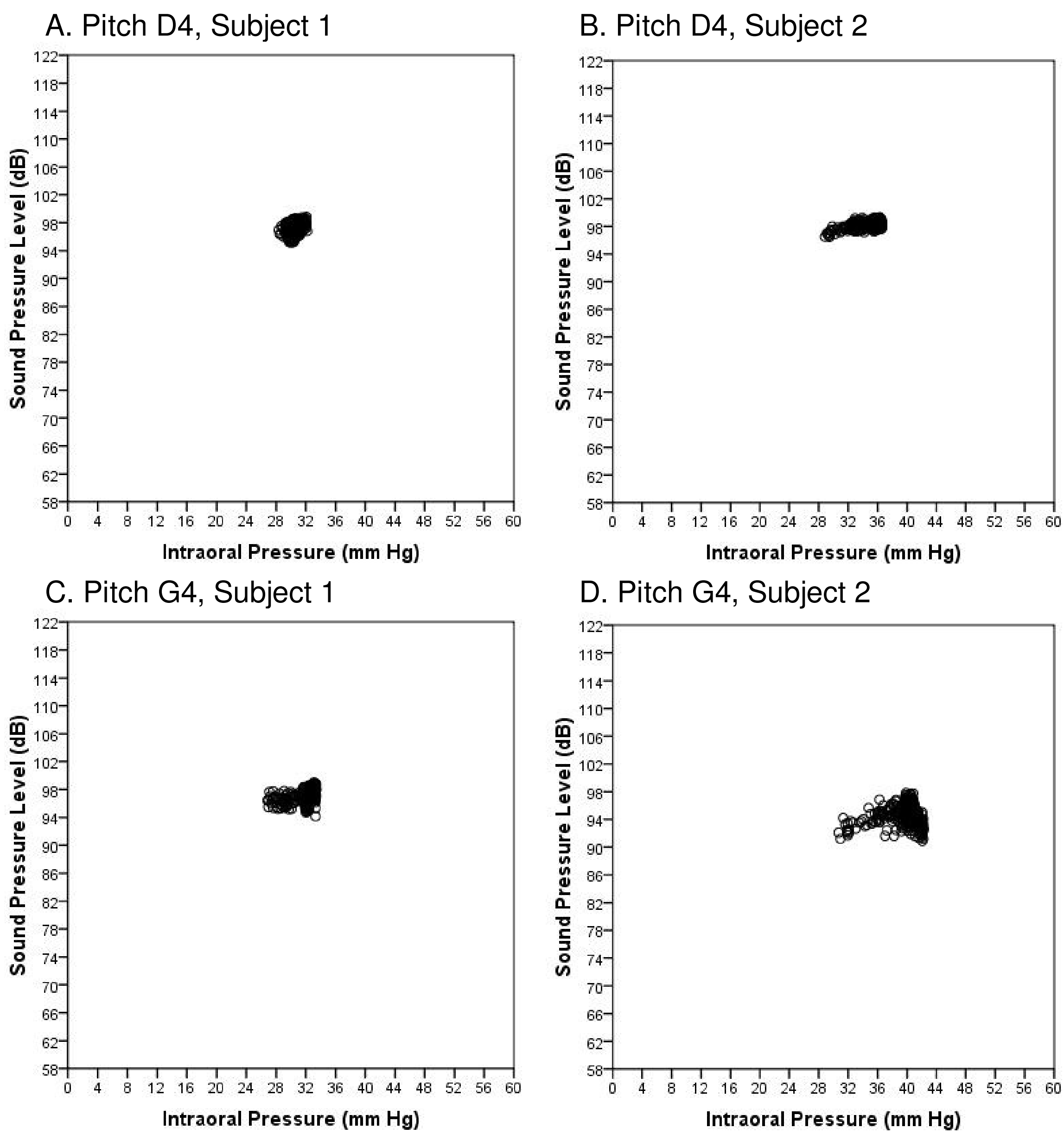

Figure 36. Pitches D4 and G4 (Straight) – Comparison of Subjects 1 and 2

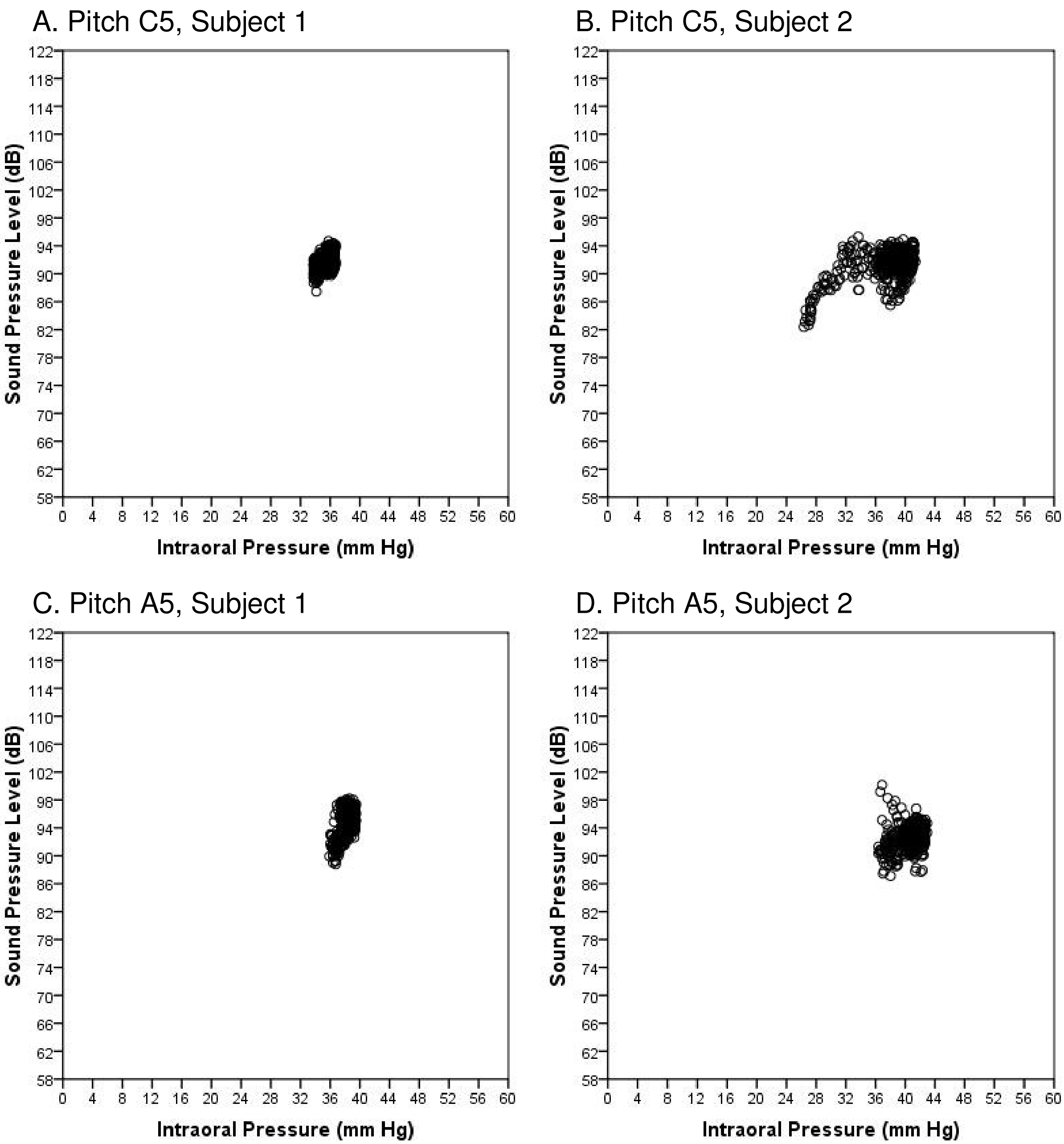

Figure 37. Pitches C5 and A5 (Straight) – Comparison of Subjects 1 and 2

This evidence is not conclusive, but does suggest that there is an improvement in physical control that comes with training and time; it is likely that this control is an important factor in the maturation of tone quality throughout an oboist’s life.

CHAPTER 6

CONCLUSION

Limitations of the Current Study

There are several areas that should be addressed when considering the significance of this project. First, this study involved only four subjects, which is not a small sample for a typical study of this kind: previous research in this field often used only one or two subjects. However, it is very likely that four subjects is too few to allow generalization to the population at large. Additionally, all of the subjects used in this study came from the oboe studio at a single American university. The American oboe tradition is noted for its wide variation in styles and sound preferences; it also varies from other playing styles around the world. Therefore, generalization from this small, somewhat homogeneous sample to the general population may not be warranted.

Second, the sound pressure (SPL) results from this study should not be compared to those from any other study that did not use the same placement for their decibel (dB) meter. Many experiments use a 1-meter or 2-meter distance for taking SPL measurements, while the dB meter for this project was 8-9 inches from the oboe bell at rest. This resting distance may have changed slightly based on the player's movements, but I suggest that test subjects will be attempting to sit as still as possible while undergoing nasoendoscopy (FFN).

As a general rule, sound pressure decreases by 6 dB for each doubling of distance from a point sound source.[1] Directionality of sound is another factor. Bouhuys

[1] "Sound and Noise: Characteristics of Sound and the Decibel Scale; Propagation of Sound" [website], Available at: http://www.epd.gov.hk/epd/noise_education/web/ENG_EPD_HTML/m1/intro_5.html *and* /intro_6.html, accessed 12 June 2011.

found that, with a 2-meter distance between the performer and the SPL meter, the SPL only fell by 5 dB when the subject turned around and faced away from the meter.[2] I found a drop in my own measurements of approximately 4-10 dB when the SPL meter was placed 21 inches behind the performer rather than 8 inches in front. Fuks took measurements at 2 meters and then repeated the test in a reverberant chamber designed to eliminate sound attenuation; he reported measurements approximately 11-15 dB higher in the reverberant chamber.[3] All of this is to say that SPL measurements can only be compared when the data gathering process is identical.

Finally, a question could be raised about the invasiveness of the FFN procedure and whether or not the intraoral pressure (IOP) and SPL data collected during such a procedure reflect real performance conditions. The FFN technique is much less invasive than the esophageal balloon technique of the 1960s, and previous researchers have reported that their subjects tolerated the FFN procedure well and showed no impairment of their performance ability.[4] From my own participation as a subject in this study, I did not notice any impairment of my abilities due to the measuring devices. After talking with and observing the other subjects during the study and listening to the audio recordings made of each subject, I did not hear any impact on tone quality from the FFN procedure.

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[2] Arend Bouhuys, “Lung Volumes and Breathing Patterns in Wind-Instrument Players,” *Journal of Applied Physiology* 19 (1964): 969.

[3] Leonardo Fuks, “Aerodynamic Input Parameters and Sounding Properties in Naturally Blown Reed Woodwinds,” *Speech, Music and Hearing: Quarterly Progress and Status Report* 4 (1998): 2, 10.

[4] Austin I. King, Jon Ashby, and Charles Nelson, “Laryngeal Function in Wind Instrumentalists: The Woodwinds,” *Journal of Voice* 1, no. 4 (1988): 365-66; idem, “Laryngeal Function in Wind Instrumentalists: The Brass,” *Journal of Voice* 3, no. 1 (1989): 66.

Suggestions for Future Research

Based on the results I have described in the preceding chapters, several directions for continued study are obvious. First, a more detailed study of the oboe's sound envelope is needed, profiling each possible pitch to characterize (1) the location of register breaks, if any, (2) the properties of each register so defined, and (3) the linear and nonlinear segments of the sound envelope as previously described.

Second, there is a need for IOP studies that incorporate larger subject populations and attempt to describe the effects of (1) age, experience and national playing styles of the subjects, (2) oboe make and model, and variations within a single brand of oboe, and importantly, (3) reeds of different hardness and scraping styles, and (4) removing these variables by having many subjects use the same instruments and/or reeds.

Third, the use of the vocal tract and its relationship to IOP regulation and vibrato has not been definitively explained; the literature to date contains many studies measuring vocal tract movement or air pressure, but few studies with quantitative measurements in both areas. More research pairing vocal tract visualization with IOP data are needed, in particular to describe the role of the glottis in oboe performance.

Fourth, the static and kinetic activation thresholds of the oboe reed need to be described in detail. This study focused on the propagation segment of tone production, after initiation and before termination, but what happens in the preparatory and termination phases is arguably more interesting and certainly more intricate. Starting and ending notes well is a major challenge for young oboists; these thresholds need to be characterized across all registers on the oboe to provide as much assistance to oboe students and teachers as possible.

Finally, the way is open for further studies of musical context, using the modern technology available for data capture and analysis. As discussed in chapter 2, Fuks and Sundberg have reported that there a difference in IOP between a note played by itself and that same note when approached from below or from above. Looking at notes in their musical context has important ramifications for pedagogy, because learning to play an instrument means learning an intuitive, note-by-note evaluation of what you are hearing and comparing it to what you want to hear. The skilled performer learns to make fractional changes in technique based on the anticipated requirements of an upcoming note, interval, chord or phrase. The more information we can provide about these fractional changes, the easier it will be for students to grasp these concepts and reach the goal of making their own informed pedagogical and interpretive decisions.

Concluding Remarks

Most music teachers have strong conceptions about sound production, particularly in the oboe-playing community in the United States, where tone color is considered to be of primary importance (as opposed to technical agility or other performance values). Through research and analysis we, as teachers and performers, are given the opportunity to examine how sound is really produced, and to compare it with our various hypotheses (learned from experience or tradition). Sometimes we will be proven correct, and sometimes not. A true understanding of the body’s function in sound production, based on empirical evaluation rather than on impressions and tradition, will help teachers streamline the learning process for their students and train efficient performers who understand how to use their resources effectively.

A further rationale for building the body of knowledge available to performers is the potential for performance-related injuries. The musician is exposed to risk factors that may lead to injury in several areas, including hearing damage and musculoskeletal problems such as dystonias or repetitive strain injuries. An issue more directly related to the present study is the problem of velopharyngeal insufficiency (VPI), a condition where the soft palate is unable to completely seal the oronasal cavity during exhalation, allowing air to leak out through the nose.[5] This can occur during speech in individuals with a cleft palate, but can also appear during higher-pressure conditions such as wind instrument performance. This leakage of air can make it difficult or impossible to maintain the elevated IOP needed for wind playing.[6] There is no evidence that wind playing causes this deficiency, but it is possible that the higher demand on the velopharyngeal mechanism during performance could reveal a structural weakness that is not obvious during normal usage.

Current research has not assessed air pressure limits for performers to avoid development of VPI, but it stands to reason that the performer should avoid blowing with more pressure than is needed to accomplish their musical goal. In relation to the current study, the results shown in figures 22 and 23 describe the nonlinear sound profile of the oboe. There is a clear limit of IOP that, once exceeded, continuing to increase air pressure yields only minor increases in sound pressure. Therefore, the oboist should try

[5] Alison Evans, Bronwen Ackermann, and Tim Driscoll, “Functional Anatomy of the Soft Palate Applied to Wind Playing,” *Medical Problems of Performing Artists* 25 no. 4 (2010): 183.

[6] Jaroy Weber, Jr. and Robert A. Chase, “Stress Velopharyngeal Incompetence in an Oboe Player,” *Cleft Palate Journal* 7 (1970): 858.

to produce their tone with the minimum blowing pressure that will deliver the desired pitch and tone quality.[7] Such efficiency will certainly enable the player to extend their fatigue threshold, and may also aid in minimizing the potential for injury to the structures of the airway.

When we as teachers deepen our understanding of anatomy, physiology, and their function in performance, we become better-equipped to train students correctly. We must educate our students to think critically about what they are doing, and not simply follow our patterns without evaluation. If I tell a student that they need to exhale by pushing from their abdomen and not constricting their throat, I should be able to explain not just how this will improve their sound, but why it is beneficial or necessary from a physical perspective. It is more important to equip students to evaluate their own work than to simply teach them one particular method. If they are taught to continually assess themselves, both artistically and empirically, they will be able to identify pitfalls earlier and make well thought-out adjustments to their technique, in the presence or absence of a teacher. The more knowledge we can gain and impart about the biology and physiology of performance, the better our ability to make good musical choices will become.

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[7] Martin Schuring, *Oboe Art & Method* (New York: Oxford University Press, 2009), 9.

APPENDIX

RESEARCH CONSENT FORM WITH IRB APPROVAL

UNIVERSITY OF NORTH TEXAS
COMMITTEE FOR THE PROTECTION OF HUMAN SUBJECTS
RESEARCH CONSENT FORM

Subject Name: ______________________________ Date: __________________

Title of Study: The Effect of Articulation, Pitch and Loudness on Vocal Tract Movements and Intraoral Pressure During Wind Instrument Performance

Principal Investigator: Fang-Ling Lu, Ph.D.

Co-Investigator: Michael Adduci, M.M., Kris Chesky, Ph.D.

Before agreeing to participate in this research study, it is important that you read and understand the following explanation of the proposed procedures. It describes the procedures, benefits, risks and discomforts of the study. It also describes your right to withdraw from the study at any time. It is important for you to understand that no guarantees or assurances can be made as to the results of the study.

PURPOSE OF THE STUDY:

The purpose of this study is to look at how musicians perform on the bassoon and the oboe, and to find out what behaviors during performance may cause health problems. Some instrumentalists have complained of muscle tension and fatigue, as well as pain and discomfort around the head and neck area. However, there has been no research on the health issues related to performance on these instruments.

PROCEDURES OF THE STUDY:

You will be paid $50 for your participation in this study, which will last about two hours.

The study will take place in the Voice Laboratory located in the Department of Speech & Hearing Sciences at the UNT. In the beginning of study, you will read and sign an informed consent form to participate. You will also fill out a survey asking about your musical experience and medical history. You will then be asked to rehearse a set of simple musical exercises designed for the chosen instrument. The practice helps familiarize you to the tasks in the study.

After your practice, the researcher will set up closed circuit TV cameras in the room to capture the video images. A microphone will be used to capture the audio portion of the data. In the study, you will go through two procedures concurrently while you perform on the instrument. These procedures are designed to collect two types of the data, real-time images of the vocal tract and pressure changes in the mouth. To record a real-time visual display of your vocal tract, you will undergo a procedure called "flexible fiberoptic nasendoscopy" (FFN). FFN has been a standard technique for evaluating patients with voice or swallowing problems. In the FFN procedure, the researcher will pass a scope with 3.5 mm diameter, through your nose, to the back of your mouth where internal structures of the throat can be clearly viewed. To collect data on the intraoral pressure changes, you will wear a headset mounted with a plastic tube with 1-mm diameter. The tube will be rested at the corner of your mouth during performance. In all, you will play the musical exercises three times, so the researcher will be able to record the vocal tract images at three locations and obtain three sets of pressure data.

PROCEDURES/ELEMENTS THAT MAY RESULT IN DISCOMFORT / INCONVENIENCE OR MAY BE ASSOCIATED WITH FORSEEABLE RISKS:

There are no known risks involved from external video and audio recordings in the study.

In the FFN procedure, the researcher will pass a flexible scope into the nose and through the nasal chamber. In the process, some people may have a little unpleasant feeling in the nasal chamber, whereas others may develop a gagged feeling. In either case, the researcher can apply one or two sprays of a numbing medicine (Lidocaine) to numb the thin tissue layer in your nose to ease discomfort. Only in rare cases, the scope may damage tiny blood vessels inside the thin tissue layer of the nose, which may cause minor nasal bleeding. Therefore, any person with a history of blood problems will not be subject to the FNN procedure. The blood-related problems may include blood disease, bleeding tendency, or recent use of blood-thinning drugs.

In the FFN procedure, the researcher will take careful steps to avoid the spread of contagious disease. Multiple-use equipment will be cleaned and disinfected before each use. The researcher will follow the universal infection control guidelines in the cleaning process. Thus, there will only be negligible risk for infection from the FFN procedure.

Measuring the intraoral pressure via a thin tube set at the corner of the lips is a harmless procedure. A mounting device will help direct and maintain the tube towards the corner of your lips. If the thin tube should stray from the corner of the lips to the center, there is a minimal risk of damage to the musical instrument.

BENEFITS TO YOU OR OTHERS:

By participating in this study, you will contribute to the understanding of how woodwind musicians perform. This information will help health care professionals become more attentive to the health problems associated with instrumental performance. This information will also benefit you and music teachers in improving performance skills and taking preventive measures for potential health risks.

CONFIDENTIALITY OF RESEARCH RECORDS:

All precautions will be taken to maintain the confidentiality of your personal and medical information. All data records will refer to you only by an assigned number in the study. Information gained from this study will be released only to the researchers and, if appropriate, to your physician and sponsors of the study, or as required by law. The results of this study may be published in a scientific or music journal without identifying you by name or other identifying information. Similarly, video and audio recordings collected during the study may be used in presentation of the study's findings, without identifying you by name or other identifying information.

REVIEW FOR PROTECTION OF PARTICIPANTS:

The research study has been reviewed and approved by the UNT Committee for the Protection of Human Subjects (940) 565-3940.

RESEARCH SUBJECTS' RIGHTS: I have read or have had read to me all of the above.

________________ has explained the study to me and answered all of my questions. I have been told the risks or discomforts and possible benefits of the study.

I understand that I do not have to take part in this study, and my refusal to participate will involve no penalty or loss of rights to which I am entitled. I may withdraw at any time without penalty or loss of benefits to which I am entitled. The study personnel can stop my participation at any time if it appears to be harmful to me, if I fail to follow directions for participation in the study, if it is discovered that I do not meet the study requirements, or if the study is cancelled.

In case there are problems or questions, I have been told I can call F. Ling Lu, Ph.D. in the Department of Speech and Hearing Sciences at [redacted] or Kris Chesky, Ph.D. at the College of Music at [redacted]. I understand my rights as a research subject, and I voluntarily consent to participate in this study. I understand what the study is about and how and why it is being done. I will receive a signed copy of this consent form.

______________________________ ______________________________

Subject's Signature Date

______________________________ ______________________________

Signature of Witness Date

APPROVED BY THE UNT IRB
FROM 2/4/04 TO 2/3/05

For the Investigator or Designee:

I certify that I have reviewed the contents of this form with the person signing above, who, in my opinion, understood the explanation. I have explained the known benefits and risks of the research.

______________________________ ______________________________

Principal Investigator's Signature Date

Research Consent Form- Page 3 of 3 _______ Participant's initials

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