2014

Human Perception of Piano Timbre Variations Relative to the Piano's Dynamic Range

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HUMAN PERCEPTION OF PIANO TIMBRE VARIATIONS RELATIVE TO THE PIANO'S DYNAMIC RANGE

A Monograph

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor in Musical Arts

in

The School of Music

by
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December 2014

To my wife, Cléusia;

To my son, Walter;

To my daughter, Clara,

For boosting my energy with their love.

ACKNOWLEDGEMENTS

First, I would like to thank my parents Clenilson and Soliman for believing that I was telling the truth when I asked to take piano lessons at the age of four. I also thank my brothers Pedro, Alisson, Clenilson, my mother-in-law Stefana, and my brother-in-law Robinson, along with his wife Rachel, for their trips to the USA to help my family, and for their constant moral and spiritual support.

I would like to thank Dr. Arlin Horton, Dr. Troy Shoemaker, and Dr. Raylene Cochran from Pensacola Christian College for helping me with my teaching schedule during these years of travelling back and forth between Florida and Louisiana. I would like to thank my professor Michael Gurt for being always an encouragement and an exemplar pianist.

Thanks to Daisy de Lucca Jaffé for inspiring me to keep learning, working, and enjoying life. Thanks to Dr. Marcio de Queiroz, Dr. Willis Delony, and Dr. Bill Grimes for your time, your knowledge, and for agreeing to be part of my committee. Thank you Dr. James Byo, Dr. Edgar Berdahl, Dr. Jesse Alison, and Dr.Joel Porcher, for your important insight.

Thanks to Dale Holler, Bill Kelley, Zak Berkowitz, Dr. Ben Lane, and Michelle Joseph for your “hands on” help.

Thanks to Elias Jordão (*in memoriam*), my dear grandpa, who taught me how to use a screwdriver and how to make one when one is not available.

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ABBREVIATIONS

ca.	*circa*
dB	decibel
f	*forte*
ff	*fortissimo*
ft	foot
g	grams / acceleration of gravity (if part of a formula)
Hz	Herz
In.	inches
JND	just noticeable difference
m	mass
mf	*mezzo forte*
mp	*mezzo piano*
N	Newton
pp	*pianissimo*
SPL	sound pressure level
W	weight

ABSTRACT

The purpose of this study was to investigate the perception of brightness as it relates to loudness variations in piano tone. A single note was recorded with multiple intensities and used as the stimuli. I normalized all recorded notes to be perceived with the same volume and with the same duration. Consequently, the tone quality could be evaluated without the influence of loudness. Professional musicians and music students were invited to participate. I designed a mechanical apparatus, which produced a measured amount of force applied to the piano key. This device was used to record an intensity range of approximately 23 dB Sound Pressure Level (SPL) from a single key in a Yamaha C2 grand piano. Subjects listened to recordings arranged two by two, and then chose the brightest tone of the pair.

The study found that participants easily matched (over 90%) a louder sound to a brighter tone when listening to dynamic ranges larger than 4.9 dB SPL. Participants had more difficulty in choosing the brightest tones from pairs with smaller differences in dynamics (73.8% of correct matching when listening to changes of only 1.73 dB SPL). The smallest differences in intensity levels produced results indicating the crossing of a threshold in the perception of brightness. In psychophysics, this threshold is called the just noticeable difference (JND) and it is defined as the smallest intensity variation that subjects can perceive 50% of the time.[1]

1. Reid Hastie and Robyn M. Dawes, *Rational Choice in an Uncertain World* (Thousand Oaks, CA: Sage Publications, 2001), 213–22.

CHAPTER 1: INTRODUCTION

If someone is asked to make a list of the basic components of music, elements such as pitch, rhythm, dynamics, articulation, and tempo would probably be heading the list. These elements are closely related to some physical aspects that are not perceived by humans exactly as they appear in nature. Relating physical variables and their numeric values to the psychological, more subjective perception of those variables has been an interesting task explored by many scientists of different areas. Gustav Fechner coined the term psychophysics to name the science that studies the behavior of the sensory system when stimulated by a physical source.[1]

In a classical music concert, a musician plays his or her instrument to stimulate the auditory system of the listener. There are basically three elements to this particular system: the source of the sound (the musician), the medium where the sound travels (the air), and the receptor of the sound (the listener).[2] If the sound emanating from the musician was perceived exactly the same by all the listeners in the music hall, psychophysics would not play an important role in the sciences, but since everyone in the hall will have a different perceptual experience, it is relevant to ask why they do.

The physical elements of a sound wave are known as vibration frequency, amplitude and waveform. Sine waves are the simplest type of wave widely used

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1. Gustav T. Fechner, *Element der Psychophysik* [Elements of Psychophysics], trans. Helmut Adler, vol. 1 (Leipzig: Breitkopf und Hartel, 1860).

2. Juan G. Roederer, “The Science of Music and the Music of Science: A Multidisciplinary Overview,” in *The Physics and Psychophysics of Music: An Introduction* (Fairbanks, AK: Springer, 2008).

in experiments of pitch and loudness perception. Frequency is related to pitch and amplitude is related to loudness. However, when asking a person about his or her own perception of the quality of the same sound, the description might include words such as smooth, rough, hollow, full, mellow, bright, harsh, strident, dull, strings-like, brass-like, etc. All these later characteristics are adjectives that help a listener recognize and describe the timbre that is being heard.[3]

Studies relating frequency to pitch perception and amplitude to loudness have been conducted quite successfully.[4] Although timbre has been researched just as well as frequency and amplitude, trying to quantify timbre or simply exploring it becomes a more laborious task because of its complexity and multidimensional nature. Variations in loudness, pitch and waveform can change timbre perception.[5] Otto Ortmann had already recognized that the quality or timbre of a sound is not a new attribute to the known physical principles of frequency, intensity, and the duration of the sound, but a resultant of these components, which can vary independently.[6]

Timbre and Brightness

Measuring tone qualities is a much more challenging task than to measure a tone's other known components such as sound pressure level or vibration frequency. According to the American National Standards Institute, "timbre is that

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3. Donald Hall, *Musical Acoustics*, 3rd ed. (Pacific Grove: Brooks/Cole, 2002).

4. S.S. Stevens, *Psychophysics: Introduction to Its Peceptual, Neural, and Social Prospects*, ed. Geraldine Stevens, 2nd ed. (Piscataway: Transaction Publishers, 2000).

5. Nicholas Giordano, *Physics of the Piano* (Oxford: Oxford University Press, 2010).

attribute of auditory sensation in terms of which a subject can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar." Since timbre is the result of such a complex combination of factors, what word or words would best describe differences in timbre?

When a piano note is played, the strength of partials generated by the strings is one of the main properties that assist listeners in recognizing the particular quality of the tone. However, the duration of the note, the attack and release also play an important role in the recognition of the timbre. Once the attack and release of a violin and a trumpet is removed, these two instrument timbres become very similar, according to psychoacoustic experiments.[7]

The amount of noise was also distinguished as an important element in the perception of timbre.[8] Recent studies done by Ilmoniemi, Välimäki, and Huotilainen isolated three other important components of the piano timbre: the ratio of even and odd partials, brightness, and attack time. This study observed that brightness had a direct relation with the centroid frequency (i.e., the mean frequency of the spectrum of a sound).[9]

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6. Otto Ortmann, *The Physical Basis of Piano Touch and Tone: An Experimental Investigation of the Effect of Players Touch Upon Tone of the Piano*, 1st ed. (New York: Kegan Paul, Trench, Trubner & CO., LTD., 1925).

7. David Howard and James A.S. Angus, "Hearing Timbre and Deceiving the Ear," in *Acoustics and Psychoacoustics*, 4th ed. (Oxford: Focal Press, 2009).

8. William G. Hill, "Noise in Piano Tone, a Qualitative Element," *The Musical Quarterly* 26, no. 2 (April 1940): 244–59.

9. Minna Ilmoniemi, Vesa Välimäki, and Minna Huotilainen, "Subjective Evaluation of Musical Instrument Timbre Modifications," (Joint Baltic-Nordic Acoustics Meeting, Mariehamn, Aland, 8-10 June 2004).

The timbre of the piano is generally identified in the fraction of a second after the hammer hits the strings.[10] This immediate identification from the listener is due to the strong characteristics of the components of the piano sound. However, the same piano note can produce different strengths of partials when played with different intensities. These differences produce variations or nuances in the sound, which was already perceived as a piano tone. These fine variations have led the pianist Alfred Brendel to compile a list of instruments that can be brought to mind in particular pieces if played with certain touches. Although this list was done based on his own perception and without any scientific method, it is relevant in expressing the necessity of naming such complex nuances.[11]

Because the necessity to label these nuances of the piano timbre had le d musicians to associate timbre with colors, scientists used cross-modality comparisons to help establish points of reference. S.S. Stevens found great similarities in comparing brightness (vision) and loudness (sound) relating 1 Brill (unit of light intensity, defined as the photopic threshold) to 1 Sone (unit of perceived loudness at 1000 Hz).[12] Stevens created a comparative gradation for vision and audition combined showing a dB scale from 0 to 160 dB. He demonstrated how 1 Candela/square meter of light corresponded to a normal conversation at around 65 dB; a good reading light was compared to the sound of heavy traffic, and the discomfort of direct sunlight was close to the threshold of

10. Hall, *Musical Acoustics*.

11. Alfred Brendel, "Turning the Piano Into and Orchestra," in *Alfred Brendel on Music: His Collected Essays*, new ed. (London: Aurum, 2013).

12. Stevens, *Psychophysics: Introduction to Its Peceptual, Neural, and Social Prospects*.

pain for audition at 120 dB. Based on this strong relationship in between luminance and sound intensity, plus the common use of the word *bright* to indicate higher levels of upper partials, I decided to use the word *brightness* as an indicator of timbre nuances.

Just Noticeable Differences

Humans do not perceive all physical aspects of nature. This is a puzzling dichotomy: we have many limitations in our senses, but at the same time we have compensations as well. Humans cannot hear tones that are too weak or vibrations that are too high or too low in frequency; however, we can hear fundamentals in complex tones that are not even physically present. Humans perceive clearly frequencies ranging from 2 to 5 KHz. A sound with an intensity of 10^{-12} W/m^2 is considered to be the most faint sound a human can hear, although most of us can only hear sounds with intensity levels higher than 10 or 20 dB SPL. The concept that human audition perceives frequencies from 20 Hz to 20 KHz is widely spread, but these are just round numbers used to facilitate memorization. The usual range for a young person is closer to 17 Hz to 18 KHz. This range rapidly decreases in adulthood dropping down to 12 KHz for women and 5 KHz for men in average when reaching 65 years old. [13]

Considering the above-mentioned range, how many differences in pitch can humans actually perceive? Is a difference of 1 Hz perceptible when we hear sounds at 12 KHz? E.H. Weber asked a similar question in 1830s and found that for a subject to perceive a stimulus to be greater that another, this stimulus would

13. Hall, *Musical Acoustics*, 94.

have to be increased by a certain ratio.[14]This principle is of extreme importance in the field of psychophysics: the just perceptible increase of a stimulus, commonly called the just noticeable difference (JND). The JND, known as Weber's law, is expressed by the general formula slightly adjusted by S.S. Stevens as follows:

$$\text{JND} = k(S + S_0)$$

Where S is the stimulus, S_0 is a small constant, and k is a constant ratio. Another important physicist named Gustav Fechner predicted that once a JND is found for different stimuli, one could attempt to make a scale using the JND as a unit.

Fechner introduced the viewpoint that JNDs can be thought as units of psychological intensity paralleled to physical intensity. Fechner also proposed that the psychological intensity is the logarithm of the physical intensity. This logarithmic relationship became known as Fechner's law. Although this law does not stand in every range and size of intensities, it is a good approximation.

The idea of measuring a sensation is not new. Hipparchus, for example, categorized six magnitudes by observing differences in color emanating from the stars ca. 125 b.C.[15] One method of determining JNDs in loudness is to pair sounds alternately, one with a fixed intensity and the other with a variable intensity.[16] After starting both sounds at the same intensity levels, one level is slightly raised until the subject indicates that one of the sounds is louder than the

14. Stevens, *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*.

15. Stevens, *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*.

16. J. David Boyle and Rudolf E. Radocy, "Psychometric Foundations," in *Measurement and Evaluation of Musical Experiences* (New York: Schirmer Books, 1987).

other by pushing a button, for example. When participants listen to big differences in intensity, it is obvious which one is louder, but when differences in intensity are very small, subjects face a much more difficult task in choosing a louder sound, and when the differences are so small that they tend to zero, the recognition of the louder tone becomes impossible. Therefore, somewhere in between larger differences and very small ones, there is a transition from absolute confidence to complete uncertainty.[17]

The researcher investigates both large and small differences and then establishes the edge where the consistency of judgment is wavering faster. The standard procedure currently used to find a JND is to ask subjects to choose a stimulus that is more intense out of two, and then find when 75% of the answers were correctly matched. By definition, the JND is the smallest intensity variation that participants can perceive 50% of the time. When they cannot distinguish a variation in intensity, they choose correctly 50% of the time due to chance.[18]

$$75\% = 50\% + \frac{1}{2} * 50\%.$$

The JND for sound intensity is generally larger for low frequencies combined with low intensities. For musical purposes, a JND varies from 0.5 to 1 dB SPL. In practical terms, this means that a variation of around 15-30% in intensity is necessary for listeners to perceive a variation in loudness, since it is known that a level difference of 1 dB is equal to an intensity ratio of 1.3, or 30% higher.[19] A similar process is done to find JNDs in frequency. Subjects listen to

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17. Hall, *Musical Acoustics*, 96.

18. Hastie and Dawes, *Rational Choice in an Uncertain World*, 213–22.

19. Hall, *Musical Acoustics*, 74-78.

pairs alternately with the same intensity to isolate frequency. Then the frequency of one stimulus is modified to determine the minimum variation necessary to perceive a difference in pitch. Results show that the JND for frequencies is 1 Hz when listening to simple sine waves below 1 KHz. For frequencies above 4 KHz JNDs increase rapidly and human perception of pitch becomes very poor with frequencies above 10 KHz. This is one of the reasons why the highest key on a piano is around 4KHz.[20]

20. Giordano, *Physics of the Piano*, 118.

CHAPTER 2: METHOD

Participants

Participants consisted of 30 professional musicians and 29 music students including 38 pianists and 21 non-pianists. Music students averaged 24 years of age, with 16 being piano students. Participants were invited to participate in a voluntary basis through the author's Facebook page or through personal e-mail invitations. The test included 33 females and 26 males. The average for years of study for students was 13.7 years, while it was 26.3 years (including years of training) for professional musicians.

Apparatus #1

Otto Ortmann in 1929, Anders Askenfelt in 1994[21], and more recently with Goebl et. al. in 2005[22] — all agree that key-surface force is what directly influences the differences in sound intensity on the piano, therefore, I attempted to design a device that would be able to play the piano at different intensities. "The complex problem of physiological mechanics as applied to piano technique resolves itself finally, into one basic question: the variations of force produced at the key-surface by the player." Otto Ortmann[23]

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21. Anders Askenfelt and E. Jansson, "From Touch to Strings Vibration: The Initial Course of the Piano Tone," *STL-QPSR* 29, no. 1 (1988).

22. Werner Goebl, Roberto Bresin, and Alexander Galembo, "Touch and Temporal Behavior of Grand Piano Actions," *Journal of the Acoustic Society of America* 118, no. 2 (August 2005).

23. Ortmann, *The Physical Basis of Piano Touch and Tone: An Experimental Investigation of the Effect of Players Touch Upon Tone of the Piano*.

This device produced a known force when performing the task of playing a note on the piano instead of using a pianist. Many studies have used humans to record the stimuli for the experiments, but measuring amounts of energy from the pianist's arms and fingers have proven to be a difficult task, producing different results within similar experiments.[24] These differences were probably due to variations in the type of sensors used to measure the force. In addition, some sensors were placed on the surface of the piano keys while others were placed in the keybed. My mechanical device had minimal losses with friction and energy transfer due to its simple design and few moving parts. Apparatus #1 was built based on the law of conservation of energy, similar to a pile driver (figure 1).

Figure 1. Apparatus #1 showing maximum displacement of the key

24. Hiroshi Kinoshita et al., "Loudness Control in Pianists as Exemplified in Keystroke Force Measurements on Different Touches," *Journal of Acoustical Society of America* 121, no. 5 (May 2007): 2959–69.

Masses would be dropped from different heights landing on the piano key. The key would move down propelling the hammer up, which will hit the strings producing a particular sound intensity. Based on the mass and height values, one is able to calculate the potential energy that a particular mass has at a particular point.[25]

Potential Energy = m*g*h

Where *m* is the mass, *g* is the acceleration of gravity (approximately 9.81 m/s^2), and *h* is the height from where the mass was dropped.

Apparatus #1 was built with a wood base suspended above the keys and with PVC pipes attached to it in a ninety degree as shown in figure 1. PVC pipe was used as a guide for metal rods to be dropped in a free fall at the keys. These metal masses had a diameter of 1,5 cm to simulate the diameter of a finger, and were cut in increments of 50 grams from 100g to 300g. All rods had a piece of a round felt glued on the bottom to prevent damage to the surface of the piano keys and also to simulate the cushion of the fingers when depressing the keys. I cut different sizes of PVC pipes to maintain a consistent height when using different masses, as seen in figure 2. Metal rods were dropped inside the PVC pipes from a flush position on the top of the pipes. Fishing lines were glued to the metal rods for easier manipulation. This system proved to be efficient in initiating the whole process, and gave consistent readings in both dB SPL and spectral comparisons. However, it also presented one problem: the masses performed well in slower speeds (similar to a pianist playing up to a *mezzo piano*), but as

25. Ian H. Johnston, *Measured Tones: The Interplay of Physics and Music*, 3rd ed. (Boca Raton, FL: CRC Press, 2009).

the energy increased, a rebound was heard of around 50 milliseconds after the initial attack. This rebound effect disrupted the tone and created a harsh timbre. I tried using different combinations with more cushion and with heavier weights, but the rebound effect was still present. Previous studies done by Kinoshita et al. verified that when pianists played with a struck touch (hitting the keys from some distance) the applied finger-force resultant when depressing the key had three peaks consistently. A pressed touch (finger in contact with the key) showed one

Figure 2. Apparatus #1 setup for recording showing different heights of the PVC pipes

steady increment of force peaking right before the maximum displacement of the key.[26] These data shows evidence of a key rebound when the key is played with

26. Kinoshita et al., "Loudness control in pianists as exemplified in keystroke force measurements on different touches," 2959–69.

a struck touch. The opposition coming from the key mechanism affected the resultant force on the key surface. It is possible that the metal rod from apparatus #1 accelerated the key too fast after the first impact, causing the rod to lose contact with the key and immediately falling back on the key again like a trampoline. This rebound took approximately 30 to 50 milliseconds.

Since the concept of working with masses gave consistent dB SPL readings, I decided to abandon this prototype and design another apparatus. A new device was needed (and built), which could hold much heavier masses, thereby reducing the speed of the initial contact with the keys to a minimum. Based on the experience with apparatus #1 and Kinoshita et al. findings, I decided to change only the masses on apparatus #2 imitating a pressed touch and eliminating the struck touch. This solution proved to be efficient in removing the rebound effect.

Apparatus #2

Apparatus #2 (figure 3) is a controlled mechanism that uses different masses to play the piano providing similar amounts of force as those exerted by a concert pianist. This device has a wood base 25x25 in. attached to a 4x4 in. post with a metal hinge attached to its top. A 1x2 in. wide wood board 32 in. long made of oak was attached to the hinge working as the “arm” of the device. Metal hooks were fixed to the bottom of the oak board to provide a place for hanging different weights commonly used in physics labs. In order to prevent bending, a steal cable was attached to the top of the oak board. A fishing leader supporting up to 80 lb of weight was engaged to a nail used as an actuator. When pulling

out the nail, the fishing leader would slip out, activating the motion of the system. A screw of approximately 9 mm in diameter was fixed at an angle of 90° to one end of the oak board, serving as a mechanical finger for the device. This screw provided a fine height adjustment for minimal bending that occurred on the top board when using heavier weights. A piece of felt was attached to tip of the screw to prevent damage to the piano key. The piece of felt also helped to simulate the natural cushion of a human finger.

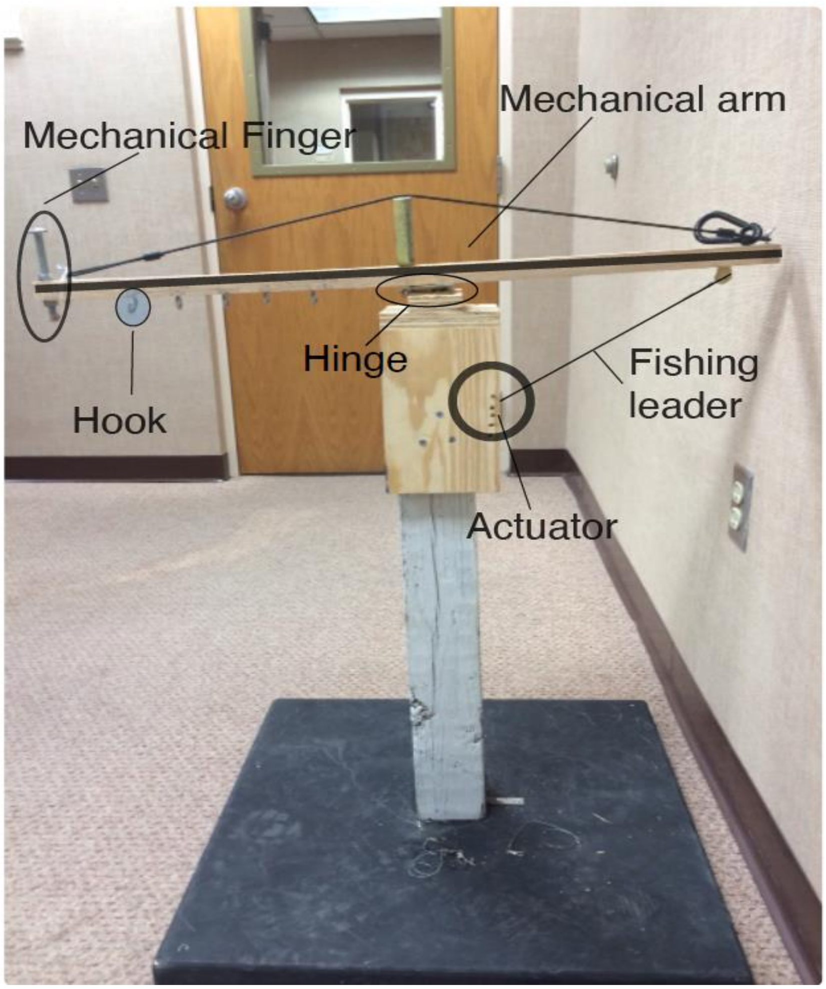

Figure 3. Apparatus #2

The top oak board measured 15 ¾ in. from the hinge to the screw used as the mechanical finger. The most distant hook was fixed at 12 in. away from the

axis of the hinge. Another hook was placed at 10 1/8 inches and the third one placed at 8 1/16 in. away from the hinge. The weight of the device at the screw was 24.5 grams. The weight necessary for moving the middle C down to midway point was 60 g with the damper pedal pressed and 80 g without applying the pedal. 50 g is considered to be a standard weight for most keys. Having a higher down weight would not be a problem since all masses would face the same resistance. The apparatus remained in balance when the mechanical finger touched the piano key.

Recording Procedure

The recording process took place in a college piano studio. Recording equipment included:

- Yamaha grand piano C2
- Apparatus #2,
- Shure SM 81 condenser microphone,
- MacBook Pro by Apple using Protools 11 software with a sampling frequency of 48 KHz and 24-bit resolution,
- Avid M-Box digital interface,
- Professional grade Phonic PAA3 dB meter with readings done every 125 milliseconds.

The microphone was placed two inches away from the strings in order to capture the quietest notes with the least amount ofexternal noise. This short distance also allowed the author to capture the noise from the hammer hitting the strings, which according to several studies is an intrinsic part of timbre

identification.[27] The Phonic dB meter was placed two feet away from the strings measuring a noise level at around 52 $\pm$ 2 dB SPL. A temperament strip was placed in the highest strings of the piano to stop sympathetic vibrations, since these keys have no dampers. The recording started after adjusting the gain for soft and loud tones and sampling the room noise for a posterior noise removal process.

Kinoshita et al.,[28] Anders Askenfelt, and E.V. Jansson[29] have done studies with sensors capable of measuring the force of the finger-key contact of concert pianists. He asked pianists to play both with a “struck” touch and with a “pressed” touch. Kinoshita et al. measurements observed that the maximum finger forces were 3 Newtons (N) for a *pianissimo* sound and 60 N for a *fortissimo* sound. To represent a force of 3 N at sea level it is necessary to have approximately a mass of 305 grams, since force (N) is equal the product of mass (Kg) times the acceleration of gravity (9.81 m/s^2).

After performing tests with different masses at different hooks, I decided to start with 160 g at the closest hook from the key. For every 100 g placed at the farthest hook from the hinge, the finger measured approximately 76 g plus a constant of 24.5 g (mass of the arm at the tip of the mechanical finger). Therefore, we can say that the resultant mass at the tip of the mechanical finger is approximately 76% of the masses placed at the 12 in. hook.The farthest hook

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27. Hill, “Noise in Piano Tone, a Qualitative Element.”

28. Kinoshita et al., “Loudness control in pianists as exemplified in keystroke force measurements on different touches,” 2959–69.

29. Askenfelt and Jansson, “From Touch to Strings Vibration: The Initial Course of the Piano Tone.”

was attached at 12 in. and the mechanical finger was at 15 ¾ in. from the axis of the hinge. The piano produced a sound intensity of 73.3 db SPL with 160 g. This was an extremely quiet sound, possibly not loud enough for musical purposes.

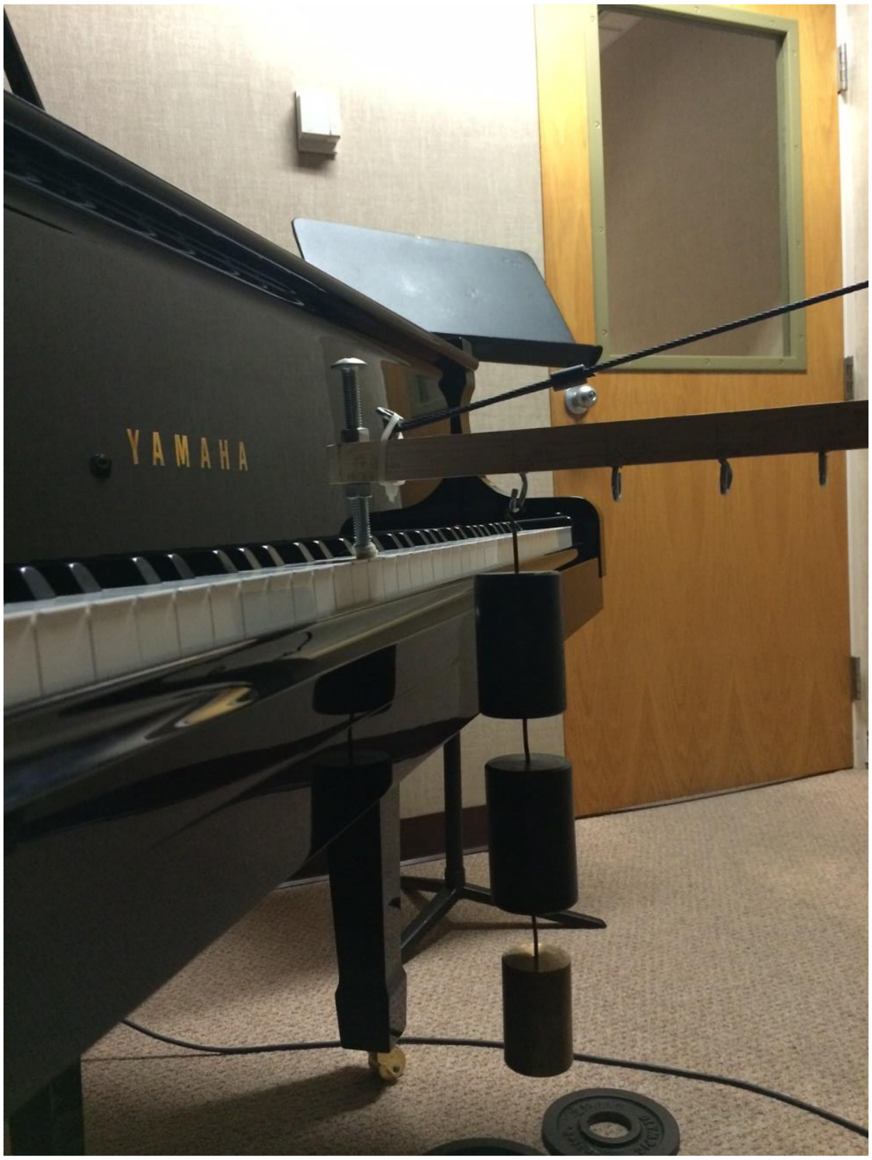

Figure 4. Apparatus #2 prepared for recording with 2.5 Kg

I raised the mass to 200 g, 240 g, and then 320 g. With 320 g, the piano responded with a clearer soft tone at around 82.9 dB SPL. This relationship in between weight (force) and sound intensity was consistent with the findings by Kinoshita et al. using concert pianists. The sound level produced by the 320 g

was defined as *pianissimo*. I recorded each mass three times and the average intensity was very similar among experiments. See the table 1 for the results. Recordings were done from soft to loud, using masses hooked at 12 in. from the hinge on apparatus #2 as seen on figure 4.

Preparation of the Stimuli

Sound files were edited using Avid Protools 11 and Adobe Audition version (8.0.0.120). After sampling the room and using the noise print as seen on figure 5, light bulb noises and noises from the device were removed using Adobe Audition.

After the noise removal process all files were individually normalized using Adobe's "Matching Clip Volume" tool with the option of matching the volume to the perceived loudness of -23 dB. This level was chosen based on the study done by Haack stating that "less intense presentation levels should be employed to enhance timbre discriminations."[30]

The quality of the sound samples was evaluated in order to select which samples would be included in the experiment. Numbers were then assigned to the samples from 1 to 6 according to their intensity levels in dB SPL. A lower number indicated a softer tone. The softest tone was assigned to number 1 and the loudest tone was assigned to number 6. Assignment of the numbers to masses and their intensities is displayed on table 1. Differences in sound intensities were evaluated and are shown on table 2. Sound files were exported to Avid Protools 11 in order to adjust the length of the note to 4 seconds and to

30. Paul Haack, "The Influence of Loudness on the Discrimination of Musical Sound Factors," *Journal of Research in Music Education* 23, no. 1 (Spring 1975).

add a fade out effect so every note would have the same duration and similar proportion of envelope (figure 6).

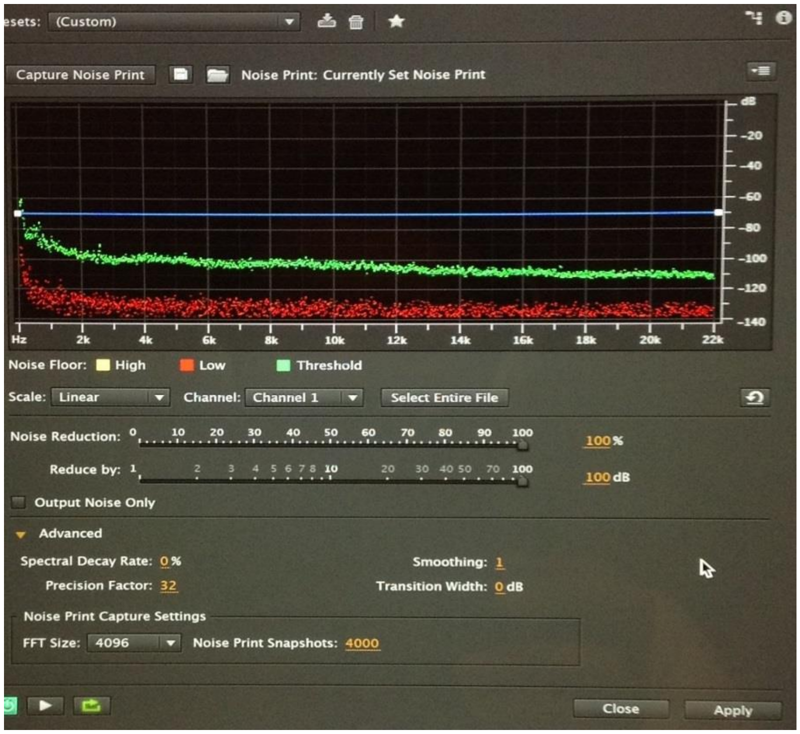

Figure 5. Noise removal settings in Adobe Audition

Table 1. Recorded tones selected for the test identified by a dynamic level number and their respective masses and intensities.

Dynamic level number	**Mass (g)**	**Intensity (dB SPL)**
1	320	82.9
2	400	85.2
3	500	86.9
4	600	88.3
5	700	89.8
6	800	91.6

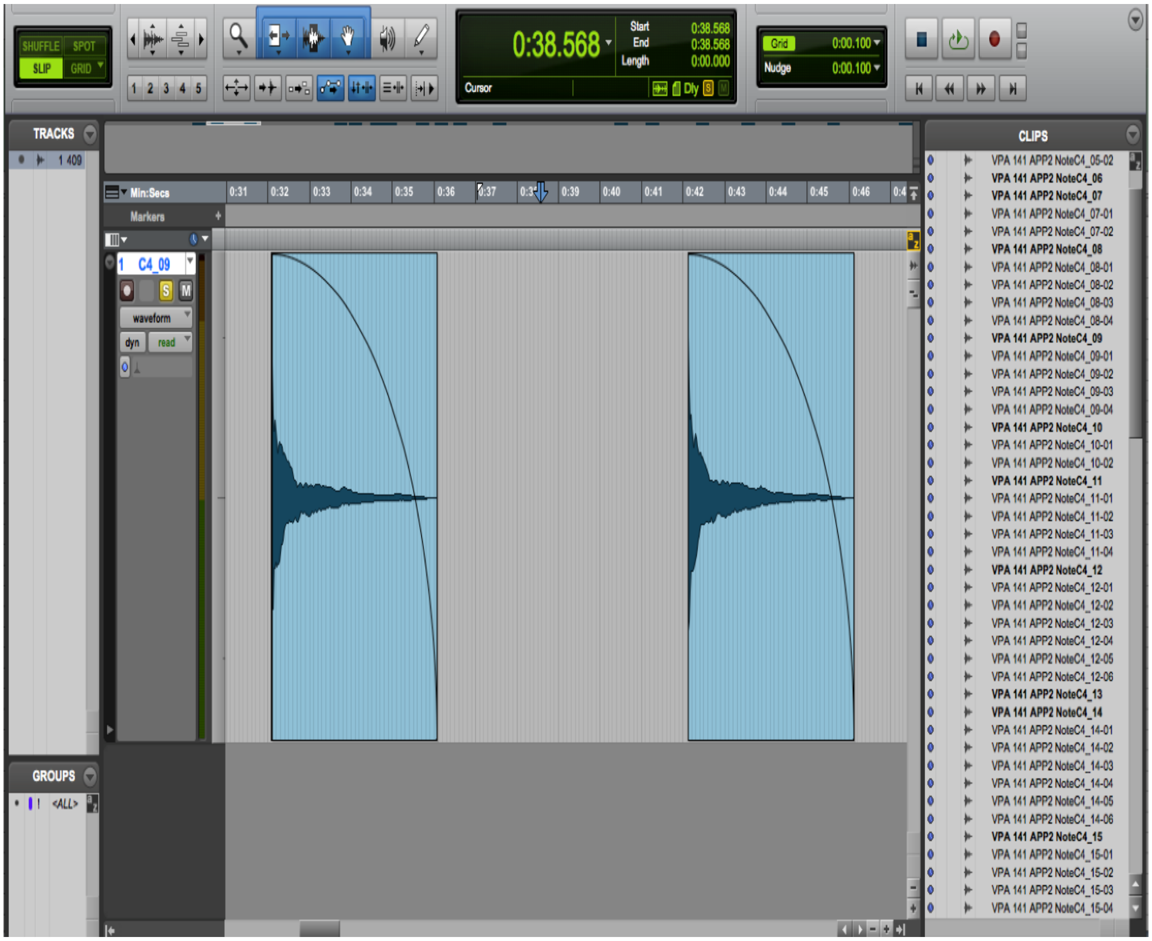

Figure 6. Envelope fade out (4 seconds)

Pilot Study

A pilot study was conducted with college music students (n=12) and professional musicians (n=8) to test experimental stimuli, website, data collection, listening equipment response, and procedures. The stimulus was recorded by a college piano professor who was asked to play one single note from *pp* to *ff* using either a “pressed” or a “struck” touch. The intensity variation recorded was approximately 23 dB SPL, which showed distinct changes in the spectrum (Figure 7).

I chose six recordings to serve as stimuli. Results demonstrated that the louder the sound, the brighter it became (the word “bright” was understood by all participants and it was defined as tones with higher and louder partials). Therefore, brightness attested to be a good indication to measure timbre variations.

Using a method of constant stimuli[31], I asked participants to go to the website designed for the study and choose the brightest note out of 15 pairings. The website interface had two circles where participants could click to play the notes as many times as necessary to perceive the brightest tone.

Table 2. Differences in volume levels and their respective intensities

Differences of volume levels	Sound intensity difference (dB SPL)	Differences of volume levels	Sound intensity difference (dB SPL)
2 - 1	2.3	6 - 4	3.3
3 - 2	1.7	4 - 1	5.4
4 - 3	1.4	5 - 2	4.6
5 - 4	1.5	6 - 3	4.7
6 - 5	1.8	5 - 1	6.9
3 - 1	4.0	6 - 2	6.4
4 - 2	3.1	6 - 1	8.7
5 - 3	2.9		

31. Stevens, *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*, 184.

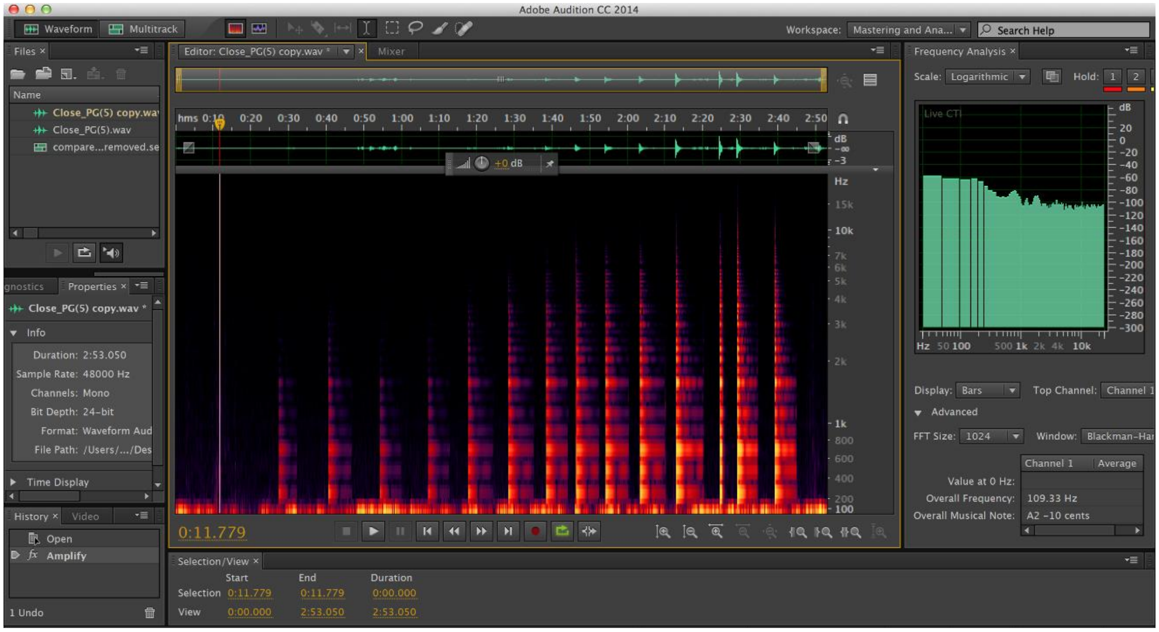

Figure 7 Visual analysis of the spectrum of a single note played repeatedly with different intensities levels. Bright red color denotes a high intensity level. Taller lines indicate higher partials present in the tone.

When participants were ready to make their choice they could simply drag the note judged the brightest into a square centered below the pair. The interface proved to be consistent and reliable on most devices, but showed some problems with the interface view in certain Android systems, as reported by some participants. Data collection showed one participant who could make a correct selection without technically clicking on the circle. This problem was addressed and fixed. Volume of the recordings was perceived as a comfortable level, without the need to make big adjustments.

Results from the pilot test were significant. They revealed that the perception of the brightness in the sound was easily recognizable. Participants matched the loudest tone to the brightest sound nearly 100% of the time. This

information led the author to limit the range of dynamics for the experiment to around 9 dB SPL, instead of the original 23 dB SPL.

Two participants had anomalous results that were inconsistent with all other participants. Problems in the website or incompatibility of hardware used to respond to the test was the most probable cause for errors. These problems were addressed by testing the website in multiple computers and portable devices and by adding a disclaimer in the first page of the study about the necessity of using around-the-ear headphones or studio computer speakers. The choice of equipment used to listen to the test was part of the data collected as well. I added a paired sample with the brighter tone clearly indicated by a yellow color. These training tones, added to the information page, should prevent any confusion about the nomenclature used in the study.

Response Interface

Participants used the method of paired comparisons[32] to discriminate between similar brightness in the tones presented. A website was created with general information about the study, detailing procedures and requirements to perform the test, the test itself, and a database to collect data from participants. A signed consent was waived by the Institutional Review Board (IRB) office at the Louisiana State University based on my documents stating that participants would not be harmed with extremely loud sounds during any of the listening procedures of the test (see appendix). Participants could listen to a pairing example similar to the ones used in the test by clicking in two separate circles as

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32. Boyle and Radocy, *Measurement and Evaluation of Musical Experiences*.

many times as they wanted in the information page. Each circle played one particular piano tone, one brighter than the other. The brighter tone in the example was played when subjects pressed the yellow circle shown in the appendix. Although anonymity was assured, participants were asked to enter data such as gender, age, instrument proficiency, years of experience, and whether professional, student, or non-musician. The test required an over-the-ear headphone or a monitor speaker, although there was no guarantee that all subjects fulfilled this requirement.

The test began in the following page where participants were asked to click on two separate circles to hear the comparisons of both tones. These tones could be played at any time; it was not necessary to wait for one sound to be over to start the new one. Each circle would play a piano tone randomly chosen out of six different possibilities. Participants could click as many times as needed in order to make a selection of the brightest tone. The test would automatically proceed to the next pairing once the brightest tone was chosen and dragged to the square below the pair. I chose six different intensity tones based on the six most commonly written dynamic levels in music (*pp, p, mp, mf, f, ff)*. Participants listened to fifteen pairs in order to have comparisons from all six sampled tones as presented by table 1.

Three extra pairings were added: one to detect whether there was a significant difference between a pianist generated tone and a device generated tone, and two pairs with exactly the same tone, forcing subjects to make a selection in a “two-alternative forced-choice” (2AFC). This 2AFC should result in

a 50/50 random choice or it would detect a different type of population if not a 50/50 result.[33] See appendix for pictures of the test webpages.

Table 3. Tone pairings

1-2	1-3	1-4	1-5	1-6
2-3	2-4	2-5	2-6	
3-4	3-5	3-6		
4-5	4-6			
5-6				

Experimental Procedures

Music faculty and music students from different colleges were invited to participate in this study via personal e-mail or through Facebook. The invitation explained the purpose, goals, and average duration of the test. The invitation also had a link to the website designed for the study, which was hosted at www.zakberkowitz.com/piano. Participants heard eighteen pairs of stimuli during the test. All tones heard were the recording of a single note (middle C) played on a Yamaha C2 grand piano with different intensities, but normalized to sound at the same volume. All participants heard exactly the same pairings, but every test was presented in a different order.

Participants were told that the purpose of the study was to investigate how variations in the sound intensity of the piano affected the perception of brightness in the timbre. They were also informed that their assignment was to evaluate two

33. Hall, *Musical Acoustics*,95.

tones presented one at a time and decide which one of the two was the brighter one. They were given the opportunity to listen to a comparison of two tones, one brighter than the other, with unlimited repeated listenings prior to the start of the test. All parts of the test, including forms and familiarization with the interface should take around 5 minutes to complete.

CHAPTER 3: RESULTS

Raw data measured how many times subjects listened to the notes in order to make a selection, and whether the selection of the brightest tone matched the highest intensity of the pair. When subjects matched brightness to loudness correctly, the computer automatically assigned a number 1. When the selection did not match the brightest to the loudest, a number 0 was assigned. Alpha level of .05 was used for all statistical analysis. Data was analyzed using the statistics software SPSS (version 22). I found no significant differences when comparing males and females, $t(869) = 0.38, p=0.704.$ Having combined the results of all of the listening opportunities, the data in Table 4 shows that men did not detect differences in the brightness of the piano tones at a different rate from women. The results of the comparison between devices used to complete the test (headphones or speaker) also found no significant differences, $t(869) = 0.75,$ $p=0.456$. Those using headphones did not detect any differences in brightness in a different rate from those who used speakers. When comparing professional musicians (n=30) with music students (n=29), the results did show significant differences in the perception of brightness, $t(869)=3.53, p=0.00044.$ In the overall comparison between pianists and non-pianists, I also found significant differences, $t(829) = 5.68$, $p < 0.001$.

- Percent correct for pianists: 462/555 = .832
- Percent correct for others: 267/285 = .937

This was an unexpected result: pianists perceived the brightness of the tones in a lower percentage rate than non-pianists. Further investigation would

be necessary to see whether years of experience from the non-pianists is playing a greater role in this comparison or not.

Table 4. Gender comparison

Gender	No.Correct	n	Prop	Std. Dev.	t	Sig.
Male	317	375	84.5%	0.0258	13.37	6.47824E-34
Female	412	495	83.2%	0.0225	14.79	1.56936E-41
Difference			1.30%	0.034230355	0.38	0.703982638

Intensity Changes Relative to Mass Changes

Different intensities were recorded for every change of mass in apparatus #2. Masses had to be large enough to produce a force capable of moving the key down with a vertical speed of approximately 0.5 m/s.[34] Means of the intensities produced by different masses listed on Table 5. Sounds produced with 160 g were very weak at around 74 dB SPL. Results show that masses equal or larger than 1400 g produced loud tones with very similar sound intensities. These findings are comparable to what Kinoshita et al. revealed in their research with concert pianists, who demonstrated that the efficiency of the force applied to produce a *fortissimo* was only 60% and the force producing similar results in sound intensity ranged from around 20 to 50 N.[35]

Figure 7 shows that once masses reach values at around 1400 grams, the sound intensity stabilized to a level of approximately 95 dB SPL. The dotted line suggests an idea of how close the relationship force/intensity compares to a logarithm function.

34. Giordano, *Physics of the Piano*, 82.

35. Kinoshita et al., “Loudness control in pianists as exemplified in keystroke force measurements on different touches,” 2959–69.

Table 5. Average Intensities for specific masses

Mass (g)	Intensity in dB SPL	Mass (g)	Intensity in dB SPL	Mass (g)	Intensity in dB SPL
160	74.2	**700**	90.0	**2000**	95.5
200	78.3	**800**	91.8	**2500**	96.2
240	80.3	**900**	92.5	**3000**	96.1
320	82.9	**1000**	93.1	**3500**	96.2
400	85.2	**1200**	93.7	**4000**	95.0
500	86.8	**1400**	95.1	**4500**	95.4
600	88.5	**1600**	95.4		

Number of Clicks Compared to Intensity Differences

A one-way analysis of variance (ANOVA) showed that there is a significant correlation in between the number of clicks used to make a decision (difficulty to perceive differences in brightness) and the range in dynamics (intensity), $F(4,850)=20.38$, $p<.001$. Figure 8 show that fewer clicks indicated a clearer decision regarding participant's perception. The null hypothesis that there was no difference in between the perception of brightness and the differences in loudness in the piano tones was therefore, rejected.

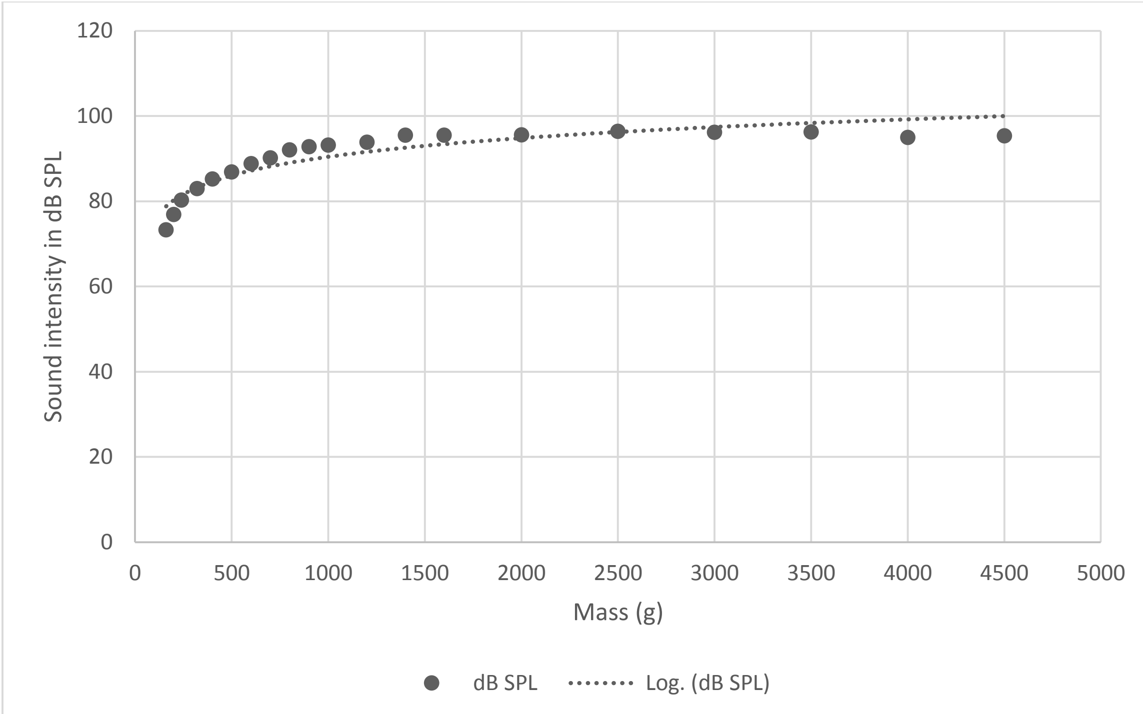

Figure 8. Mass/Sound Intensity curve

Table 6. Means for volume differences

Vol. Diff.	N	Mean	Std. Dev.	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Max
1	285	5.39	3.794	.225	4.94	5.83	2	30
2	228	4.14	2.421	.160	3.83	4.46	2	15
3	171	3.61	2.567	.196	3.23	4.00	2	20
4	114	3.19	1.876	.176	2.84	3.54	2	12
5	57	2.84	1.634	.216	2.41	3.28	2	9
Tot	855	4.24	3.015	.103	4.04	4.44	2	30

Post Hoc tests were conducted to find where the differences were. Table 7 shows these differences by indicating them with an asterisk. Means of the

number of clicks compared to the volume differences show a clear negative slope plotted on Figure 9.

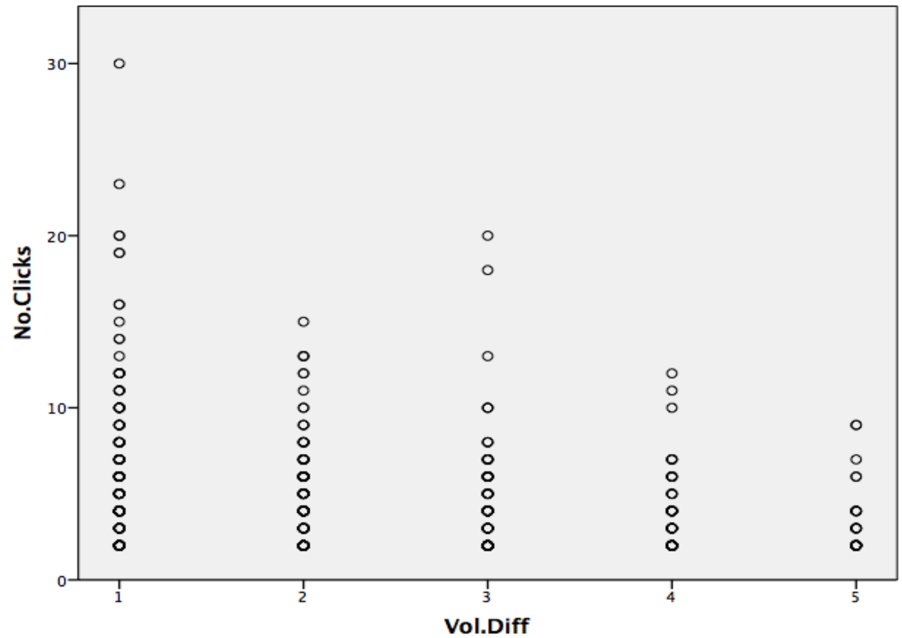

Figure 9. Number of clicks necessary in order to make a decision relative to volume difference levels.

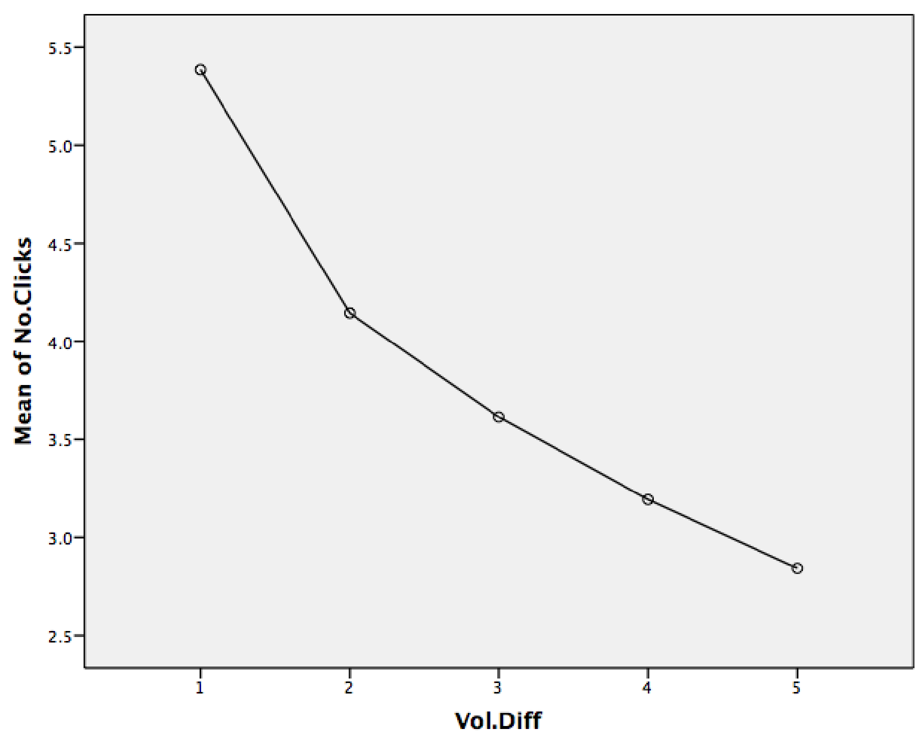

Figure 10. Mean of number of clicks showing it was harder to make a choice with smaller volume differences.

Table 7. *Post Hoc* analysis showing where significant differences were found among the 5 tested ranges

(I) Vol.Diff	(J) Vol.Diff	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	1.241*	.257	.000	.52	1.96
	3	1.772*	.279	.000	.99	2.56
	4	2.193*	.320	.000	1.29	3.09
	5	2.544*	.419	.000	1.36	3.72
2	1	-1.241*	.257	.000	-1.96	-.52
	3	.531	.292	.696	-.29	1.35
	4	.952*	.331	.042	.02	1.88
	5	1.303*	.428	.024	.10	2.51
3	1	-1.772*	.279	.000	-2.56	-.99
	2	-.531	.292	.696	-1.35	.29
	4	.421	.349	1.000	-.56	1.40
	5	.772	.442	.808	-.47	2.01
4	1	-2.193*	.320	.000	-3.09	-1.29
	2	-.952*	.331	.042	-1.88	-.02
	3	-.421	.349	1.000	-1.40	.56
	5	.351	.468	1.000	-.97	1.67
5	1	-2.544*	.419	.000	-3.72	-1.36
	2	-1.303*	.428	.024	-2.51	-.10
	3	-.772	.442	.808	-2.01	.47
	4	-.351	.468	1.000	-1.67	.97

*. The mean difference is significant at the 0.05 level.

**. Bonferroni

CHAPTER 4: DISCUSSION

This study demonstrates that professional musicians and music students can perceive clear differences in the brightness of the piano tone when a single note is played with different dynamics (intensities). This question was answered by showing that the number of clicks needed to make a decision was significant, according to the one-way analysis of variance. A *post hoc* test demonstrated where the participants perceived these differences, with the test showing that it was easier for participants to determine brightness variations in larger ranges of intensities. However, there is still the question: what is the intensity range where it becomes impossible for participants to judge assertively which tone was the brightest? This question is answered when one finds a just noticeable difference (JND). Results showed that the author was close to finding a JND for brightness in the piano timbre (73.8% of correctly matched pairs with volume differences of one dynamic level). Finding a JND for brightness was not an original goalof the process; however, this extra information enhanced the scope of the present study.

Counting JNDs might be an attractive way to quantify timbre based on the brightness of a tone, but whether finding a JND or not, I was not concerned in creating such scale. Asking someone to play a note adding three JNDs of timbre sensations to a first note played seems meaningless. Conversely, it is relevant to know that musicians can perceive variations in the piano timbre only when they

listen to differences in intensity louder than a specific amount. This is an intervallic scale as proposed by S.S. Stevens.[36]

I believe it is necessary to explore a larger range of intensities in further studies to investigate how JNDs are perceived throughout the whole extent of the piano dynamics. Another consideration for further research is to verify how JNDs change relative to the frequency range of the piano, since the present study was based on a total variation of only 8.7dB SPL in between the softest and the loudest tone. The sampling was only done with one note (middle C ≅ 261 Hz). The method used in this study proved to be effective in finding differences in brightness when comparing to differences in dynamics by isolating the quality of the piano tone (timbre) from loudness and pitch variations.

Pedagogical Application

Results showed a significant difference in the perception of brightness by professional musicians when compared with music students, therefore one can conclude that this perception is something that can be learned and developed. Professionals, who had an average of 26.3 years of experience responded with a higher degree of assertion when compared to students, who had an average of 13.7 years of experience.

More Effort Doesn’t Always Means More Sound

Results regarding the amount of force used to produce different sound intensities at the piano require deeper investigation. However, as demonstrated by Kinoshita et al. in addition to the data Figure 7, it seems that in practical

36. Stevens, *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*, 48-51

terms, slight changes in effort by pianists produce great variations in intensity when playing in a soft dynamic level. Once a mechanical threshold is reached at high intensities, larger increments of force will not change the loudness in sound intensity and consequently will not change our perception of brightness.

> "The adjustment of low sound intensities clearly demanded an extremely high level of force control. Conversely, at the highest SPLs, this demands the modulation of a large force output against the key." (Kinoshita et al.)[37]

Many studies relate extra noises, like the percussive sound emanated by the finger-key contact, the key-keybed contact, and the hammer-string contact, along with the use the pedals, as sounds that influence the perception of the overall quality of the tone. [38],[39]

Final Thoughts

This study gives a clearer perspective on the long discussed controversy about piano touch versus piano tone: Is it possible to have different qualities of tone within the same dynamic range? Many other studies have investigated piano timbre scientifically both recently (Ilmonieni et al) and as long as ninety years ago (Ortmann). The purpose of this research was to evaluate brightness as an important, though not the only component of timbre. Participants could not

37. Kinoshita et al., "Loudness control in pianists as exemplified in keystroke force measurements on different touches," 2966.

38. Werner Goebl, Roberto Bresin, and Alexander Galembo, "Once Again: The Perception of Piano Touch and Tone. Can Touch Audibly Change Piano Sound Independently of Intensity?," *Proceedings of the International Symposium on Musical Acoustics* (March 31st 2004, Nara, Japan).

39. Hill, "Noise in Piano Tone, a Qualitative Element," 244–59.

detect any differences in between two tones recorded at different intensities up to reaching a variation of approximately 1.73 dB SPL (mean for differences of 1 volume level). It is then appropriate to say that no possible variation was found in piano timbre when two tones were played within approximately 1.73 dB SPL from each other. Recording minimal increments of intensity in the whole piano range using a device such as apparatus #2 is an attractive future research to be considered. One can use such recordings to find JNDs for the whole piano spectrum and create a type of timbral response curve.

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APPENDIX

Brief Parallel in Between the History of the Piano and the Development of Psychophysics

"The production of greater or less sound depends on the degree of power with which the player presses on the keys, by regulating which, not only the piano and forte are heard, but also the gradations and diversity of power, as in a violoncello…" Francesco Scipione, Marchese de Mafei in 1711.[1]

The piano provided innovations, which could not be observed otherwise in other keyboard instruments. Cristofori built the first piano, his *gravicembalo col piano e forte,* in 1709. *The* ability to play loud and soft was a great advantage for expressiveness. The piano became a favorite instrument to play chamber music due to the piano's capability to accompany at various degrees of dynamics. It was no longer necessary to thin the texture of what was been played in order to achieve softer dynamics. Although the success was not immediate, innovations and developments of the piano started to appear along the XVIII century with many builders including Silbermann's pianos. He used a different type of hammer check than the one developed in Cristofori's pianos. J.S. Bach had supposedly a good impression of Silbermann's pianos when playing in one during a visit the court of Frederick the Great in 1747.

Johann Andreas Stein, who worked for Sibermann, and his son-in-law Johann Andreas Streicher presented the next important innovation of the piano, the individual escapement action. Mozart wrote a letter to his father praising the

1. Reginald Gerig, *Famous Pianists and Their Technique*, new ed. (Bloomington, IA: Indiana University Press, 2007), 36.

importance of the escapement in the Stein pianos in 1777.[2] Improvements to the mechanism of the piano continued with several manufacturers, including the Broadwood pianos with its three strings, foot pedals for sustaining and *una corda,* and especially an extended pitch range. Beethoven approved and explored such improvements in his Piano Sonatas. The popularity of the piano grew and other features were added. Extra pedals were designed such as fagotto and harp pedals; other instruments were enclosed, controlled by the pianist, like drums and bells, but these were abandoned along the years. By 1800 Europe was producing thousands of pianos. Sébastien Érard patented the double escapement mechanism allowing the action to respond much quicker, so repeated notes could be played at faster speeds. Érard was Chopin's choice for pianos. The next important improvement came from America in 1825 from Alpheus Babcock (1785-1842) who designed and constructed the first successful iron frame.[3] Other contributions developed quickly like the over-stringing method, where bass strings crosses over the treble strings, the use of felt for the hammers, and the action for an upright piano. Technically, the finest instruments of the1850s are very closely related to the pianos built today, and yet, there are developments currently being done, such as the recent introduction of what is called a harmonic pedal. However, it does seem like the piano has reached a sort of endpoint in its evolution.

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2. Reginald Gerig, *Famous Pianists and Their Technique,* 39.

3. Stewart Gordon, *A History of Keyboard Literature* (New York: Schirmer Books, 1996), 13.

In his late piano works Beethoven seemed to want more than his own instruments could provide. He was not satisfied with the expressive limitations imposed by the pianos available to him. Just a few decades after his death, the piano industry achieved what Beethoven was waiting for. Technology and music have changed much since 1850; therefore, it is appropriate to ask why the piano has not changed lately? The answer seems to point not to a lack of creativity within piano manufacturers, but in the developments of a new area of study combining physics, psychology, and physiology. This new study developed a clearer understanding of human perception as it relates to the social and physical environment. This fusion of areas also helped to define human boundaries that still continue to be examined today including loudness, pitch, and timbre perception.[4]

Hermann Helmholtz (1821-1894) wrote his *magnum* opus in the year 1863: "*On the Sensations of Tone, as a Physiological Basis for the Theory of Music."*[5] Helmholtz investigated in depth the field of acoustics with a clear understanding of music and a strong connection with physiology. Another physician, Ernst Weber (1795-1878) proposed in his book "*De Tactu",* what became known as Weber's law: in order to perceive a stimulus as greater than another, whether it be related to the perception of weight or the perception of color, a constant percentage needed to be added to the lower stimulus. These just detectable ratios could measure psychological events based on the

4. Stevens, *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*.

5. Hermann Helmholtz, *On the Sensations of Tone* [Ellis Edition], trans. Alexander J. Ellis (New York: Dover, 1954).

perception of stimuli variations.[6] Gustav Fechner, also a physicist, was a pioneer in experimental psychology and considered to be the father of psychophysics. He wrote "*Element der Psychophysik"* in 1860.[7] Fechner expanded Weber's ideas by developing the notion of having units of perception. The combination of the ideas from Weber and Fechner lead to a logarithmic law for the growing of sensation.[8]

It seems that the modern piano has come close to the boundaries both in loudness and pitch that satisfied historically the composers and listeners of music, but this is an investigation for further studies. The modern piano encompasses the whole orchestral range in pitch and matches the orchestra loudness very closely. With such a great range it becomes virtually unnecessary to extend the piano's size or power. Science and musicians alike became more interested in the intricacy of the piano elements when these boundaries were touched or got close to be reached. The richness of the modern piano led pianists, enthusiasts, and scientists to explore the virtues of its tone, its technique, and its mechanics.

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6. Stevens, *Psychophysics.*

7. Fechner, *Element der Psychophysik* [Elements of Psychophysics].

8. Stevens, *Psychophysics.*

IRB Waived Consent Form

ACTION ON EXEMPTION APPROVAL REQUEST

Institutional Review Board
Dr. Dennis Landin, Chair
130 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.5983
irb@lsu.edu | lsu.edu/irb

TO: Pitagoras Goncalves
Music

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: September 12, 2014

RE: **IRB#** E8924

TITLE: Human Perception of Piano Timbre Variations Relative to the Piano's Dynamic Range

New Protocol/Modification/Continuation: New Protocol

Review Date: 9/12/2014

Approved_____X_____ **Disapproved**__________

Approval Date: 9/12/2014 **Approval Expiration Date:** 9/11/2017

Exemption Category/Paragraph: 2a, b

Signed Consent Waived?: Yes

Re-review frequency: (three years unless otherwise stated)

LSU Proposal Number (if applicable): __________

Protocol Matches Scope of Work in Grant proposal: (if applicable) _________

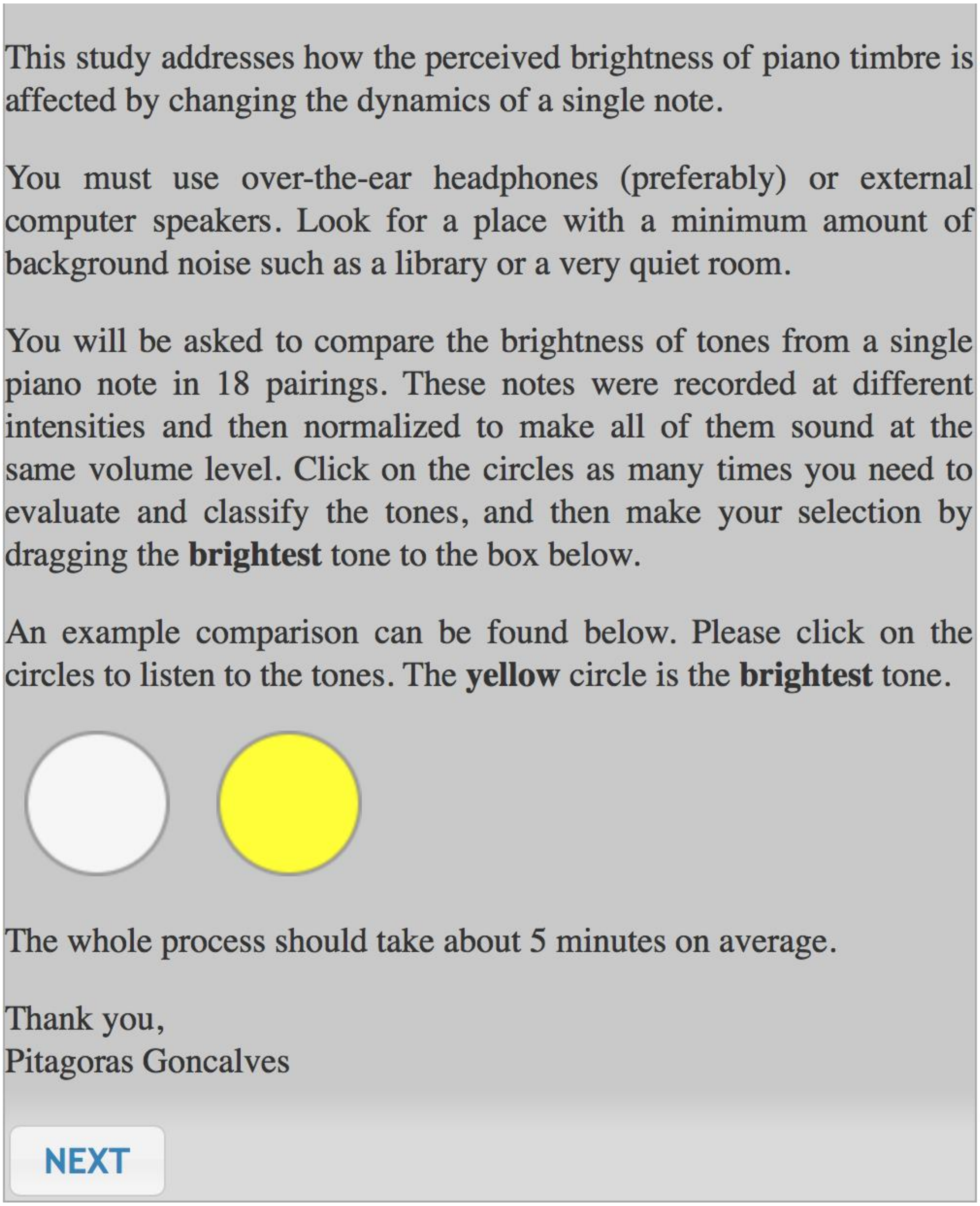
By: Dennis Landin, Chairman DLandin

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. SPECIAL NOTE:

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

Test Webpages



This study addresses how the perceived brightness of piano timbre is affected by changing the dynamics of a single note.

You must use over-the-ear headphones (preferably) or external computer speakers. Look for a place with a minimum amount of background noise such as a library or a very quiet room.

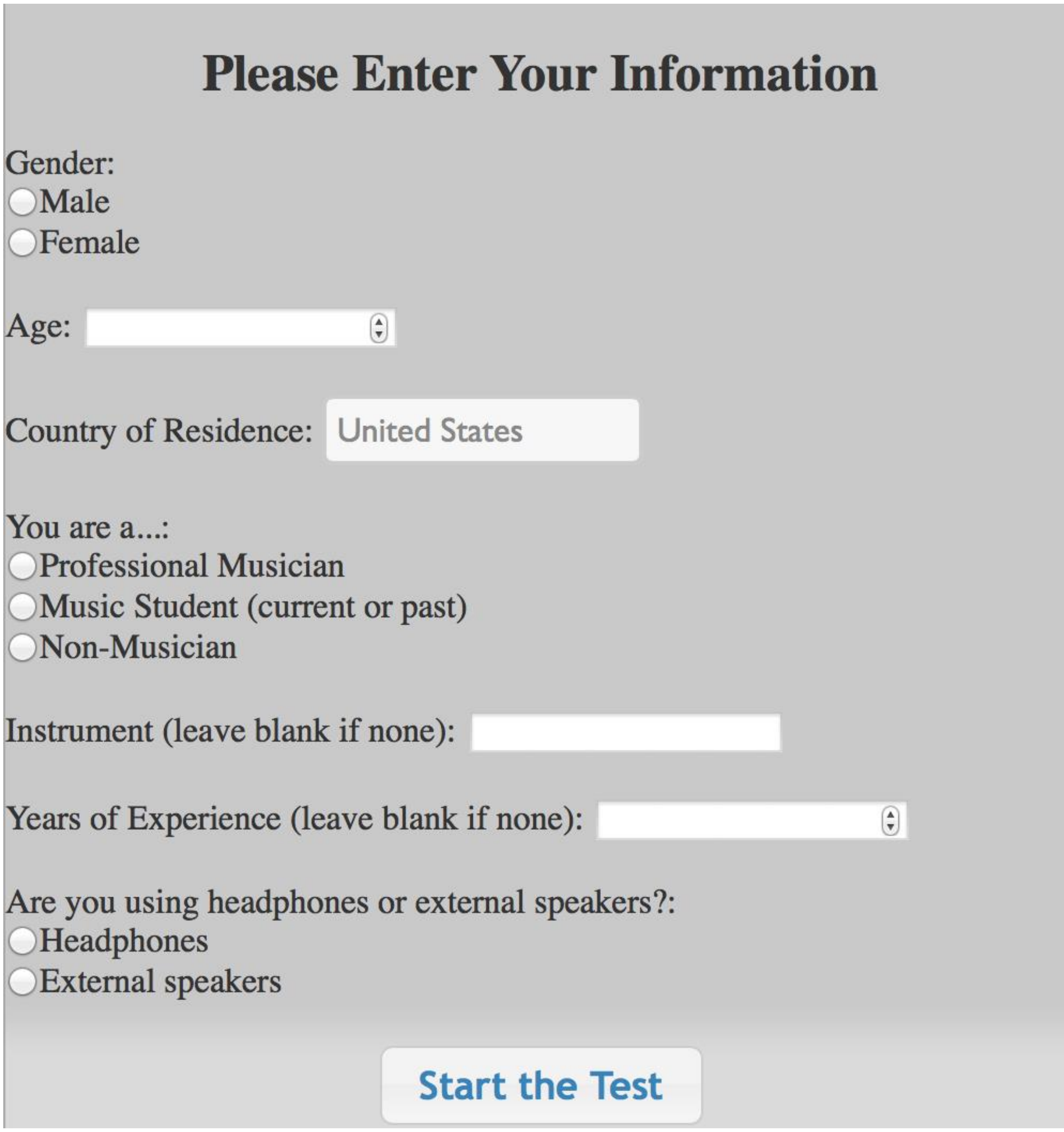
You will be asked to compare the brightness of tones from a single piano note in 18 pairings. These notes were recorded at different intensities and then normalized to make all of them sound at the same volume level. Click on the circles as many times you need to evaluate and classify the tones, and then make your selection by dragging the **brightest** tone to the box below.

An example comparison can be found below. Please click on the circles to listen to the tones. The **yellow** circle is the **brightest** tone.

The whole process should take about 5 minutes on average.

Thank you,
Pitagoras Goncalves

NEXT



Please Enter Your Information

Gender:
- Male
- Female

Age:

Country of Residence: United States

You are a....:
- Professional Musician
- Music Student (current or past)
- Non-Musician

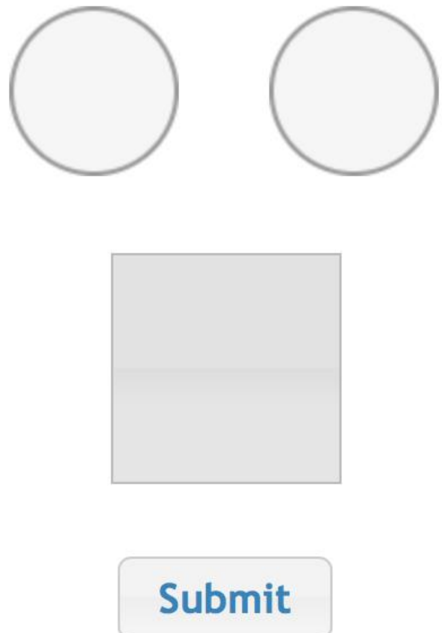
Instrument (leave blank if none):

Years of Experience (leave blank if none):

Are you using headphones or external speakers?:
- Headphones
- External speakers

Start the Test

Test 1



VITA

Pitágoras Gonçalves was born in Arapongas, Paraná, Brazil, where he began his piano studies at the age of four. He received his first musical lessons from a private teacher and at the age of six entered the Villa-Lobos conservatoire. Born in a Christian family, he started early playing for church services. After graduating from the conservatoire and receiving his high school diploma, he was accepted into the engineering program at Londrina State University and in the piano performance program at Campinas State University. Even though Pitágoras decided to major in piano; he also enrolled in engineering classes while in Campinas.

After graduating from college, he started teaching at the Carlos Gomes Conservatoire in Campinas and was appointed organist of the São Paulo First Presbyterian Church, known as the São Paulo Evangelical Cathedral.

In 1999 he moved to the USA to pursue a master’s degree at Pensacola Christian College under the guidance of Daisy de Lucca Jaffé. After graduating in 2001, both he and his wife were invited to stay as music faculty at Pensacola Christian College, where he continues to teach. Pitagoras has been active playing recitals both in US and in Brazil, besides teaching masterclasses and clinics in music schools and churches.