LARGE SCALE SOUND INSTALLATION DESIGN: PSYCHOACOUSTIC STIMULATION

An Interactive Qualifying Project Report
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by

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Abstract

The brain performs a vast amount of processing to translate the raw frequency content of incoming acoustic stimuli into the perceptual equivalent. Psychoacoustic processing can result in pitches and beats being "heard" that do not physically exist in the medium. These psychoacoustic effects were researched and then applied in a large scale sound design. The constructed installations and acoustic stimuli were designed specifically to combat sensory atrophy by exercising and reinforcing the listeners' perceptual skills.

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Chapter 1: Introduction

Natural genetic advancement through evolution and natural selection is known as the most fundamental biological mechanism for ensuring the continued survival of a species. Modern human abilities are a prime example of evolutionary success. This state of evolutionary self-awareness encourages humans to understand the biological machine that embraces millennia's worth of processed data in an effort to further our knowledge about the human body. In particular, human hearing originated as a raw sense that was essential for survival, but expanded to encompass an appreciation of a broad spectrum of modern day music. Steven Pinker's explanation for this expansion states that "music is auditory cheesecake," or nothing more than a collection of stimuli for the sole intention of evoking a pleasurable response from the listener's auditory system (514). Recognition of this recreational "preference" in what was once solely a crucial survival mechanism suggests the need for investigation into the biological and evolutionary aspects of auditory processing.

Although modern day music is culturally derived, music in general targets the high-level abilities and preferences of the human ear and brain through a complex pleasurable abstraction rather than focusing on a specific biological target. Furthermore, music is relatively young when compared to the human auditory system. In this project, we intend to create a sound design installation that focuses on stimulating innate biological functions of the human auditory system. Our sound design aims to explore the physiological phenomena that are often ignored by composers of traditional music and take the auditory system back to its evolutionary origins. Furthermore, we intend to focus on evolved psychoacoustic responses including effects such as beat induction, missing fundamental, mismatched negativity response, and brainwave entrainment. Evolution has developed the auditory system in advantageous ways. Without these abilities, we would be unable to spatially locate sounds, focus on important sounds while in a noisy environment, or hear someone's voice clearly over the telephone. In this project, special focus is devoted to auditory effects that rely on integrated brain activity, auditory processing, and cognitive adeptness.

Many studies indicate that acoustic oscillations evoke synchronous brainwave activity; this tendency for brainwaves to mimic the frequency of an external stimulus is termed brainwave entrainment. Brainwaves are electrical signals that can be directly observed with an electroencephalogram (EEG), which reveals five basic frequency bands. These electrical rhythms have been experimentally associated with various mental states such as beta waves with alertness and delta waves with deep sleep. While it is speculative that acoustic stimuli directly affect mental states, auditory-induced brainwave entrainment has been exhibited in all frequency bands, including the delta and theta bands with 1-8 Hz (Will and Berg 2007), the gamma band with 30-60 Hz (Snyder and Large 2005), and even with low frequency ultrasound at 0.44-0.67 MHz (Tyler et al. 2008).

The evolutionary benefits of many of the auditory pathway's adaptations have been well documented – ranging from increased awareness of the environment to facilitating the development of language – but the evolutionary purpose of brainwave entrainment is still unknown. It is unlikely that biological evolution pointlessly produced this phenomenon. Through evolution, this effect was or is important to human perception and is therefore entwined in the concept of being fully human. This project intends to design a sound installation that explores brainwave synchronization and entrainment, fields that could have practical applications for psychoacoustics and brain stimulation.

Chapter 2: Background Research

Much background research has been conducted to investigate the biological responses and behavior of auditory processing in humans. The results were used as the foundation and framework for the sound installation design as well as in decisions regarding the structure of the acoustic stimulation samples.

2.01: Complex Tones

To understand psychoacoustic phenomena and music in general it is necessary to draw a distinction between frequency and pitch. All sound waves have an associated frequency which is a physical parameter describing the number of oscillations per second of the wave. However, pitch is a perceptual attribute, being the auditory system's translation of frequencies into a single tone (Bendor and Wang 390). For pure tones the frequency and pitch are identical since there are no competing sound waves to alter the perceived pitch. However, most natural tones are not pure tones; rather, they are complex tones composed of multiple spectral elements.

So-called complex tones typically have spectra where the bulk of their energy is centered on a fundamental frequency and the remainder of the energy is distributed over integer harmonics of this frequency (2n, 3n, 4n, etc.). The combined perceptual effect of a complex tone is a single tone at a pitch equal to the fundamental frequency. For example, a D4 note played on guitar (~293 Hz) might result in a spectrum similar to Figure 1.

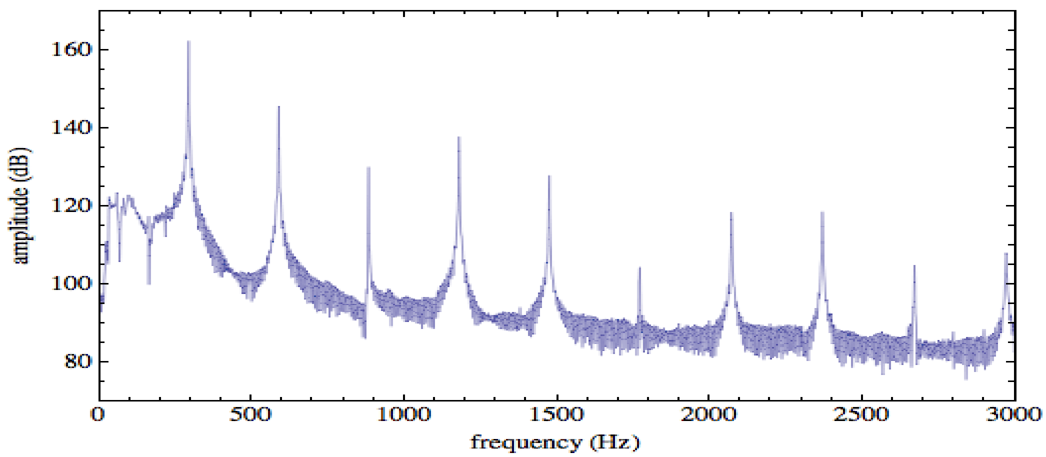

Figure 1. Frequency Spectrum of a D4 on a Guitar[1]

Here, even though the fundamental frequency is the sole determinant of pitch, the particular distribution of harmonics and their amplitudes are responsible for the tonal quality – or timbre – of the guitar as an instrument. Different instruments have different harmonic distributions which allow the ear to distinguish a C played by a clarinet versus a trumpet. Both notes have identical pitches but varying timbres. A dramatically different spectrum exists for non-tonal sounds such as percussive instruments. This is demonstrated below in Figure 2, where the frequency response of a snare drum lacks the harmonic content seen previously in a tonal instrument. Rather, the snare hit is a concentrated impulse of wide-band sound.

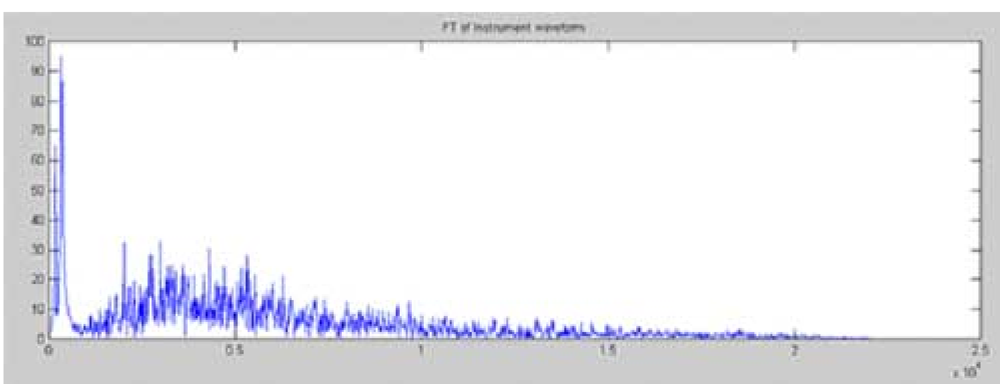

Figure 2. Frequency Spectrum of Snare Drum[2]

[1] Chapman, David. "The Sound of the African Thumb Piano." Acoustics '08 Paris. <http://www.acoustics.org/press/155th/chapman.htm>.

Complex overtones are so prevalent in traditional instruments and music that they have been given individual intervals and labels in compositions. The overtone series, as it is called when a traditional westernized musical scale is used to represent the frequencies, consists of the musical notes of a scale that correspond to the successive harmonics found in the spectrum. The spectral composition of the D4 in Figure 1 exhibits multiple notes of a scale; while fundamentally it is a D4, each harmonic overtone falls precisely into the Western scale and is a named note itself.

The fact that each overtone is itself a note is the very reason certain collections of notes belong to a scale. The successive harmonics from any given frequency can be used to complement the fundamental by accompanying the fundamental with the harmonic as its own tone. Given a C1 note, one would recognize the existence of a C2 (1st overtone), a G2 (2nd overtone), a C3 (3rd overtone), and so on (Zahm 152). However, the 7th, 11th, 13th and 14th overtones do not correspond exactly to notes in the fundamental's scale (or any note for that matter), and are roughly about a half step above or below their actual scale's degree's counterpart (Zahm 142). Along with biological limitation of the basilar membrane discussed in the remainder of this section, this factor reinforces the importance of the first six partials (or harmonics) of the fundamental. The first six fundamentals consist of octaves, fifths, and major thirds, reinforcing the major chord structure (144). The constant occurrence of this phenomenon has led to the derivation of other chord and scale structures, but the fundamental construction of each note remains the same, with emphasis on its octave, fifth, and major 3rd scale degrees. Figure 2 demonstrates the traditional musical representation of the 16 successive upper partials of a fundamental C1 note (152).

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[2] Owen, Todd. "OLD-808 Drum Machine." University of Washington. <http://todd.acmelab.org/projects/old-808.html>.

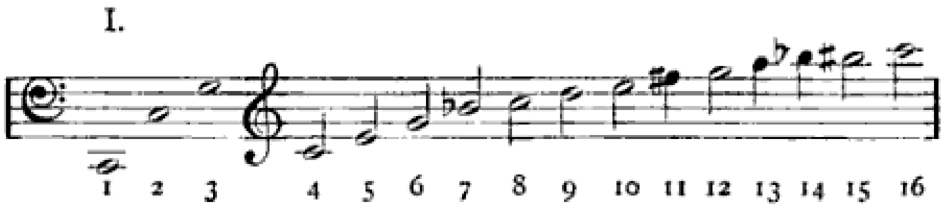

Figure 3. Overtone Series of a C1[3]

While the perceptual attributes of complex tones are well established, the biological origins of the effect are more mysterious. If multiple frequencies are entering our ears, why don't we hear multiple distinct tones? The commonly accepted answer is that a modification is performed in the inner ear. The ear consists of three main regions – the outer ear, the middle ear, and the inner ear – and the inner ear performs the first stage of frequency analysis before the sound is processed in the brain.

Sound is transferred into the inner ear by the pressure of the stapes (a small bone of the middle ear) onto the oval window. The oval window is the entrance to the cochlea, the bony spiral structure that contains the three main canals of the inner ear. The deflection of the oval window induces a pressure wave to propagate through the perilymph liquid that fills the inner ear. The wave travels through the vestibular canal towards the center of the cochlea until it reaches the apex and begins to spiral outwards again in the tympanic canal. A small third canal, the cochlear duct, lies between the two main ducts and contains hair cells which change the physical pressure waves into electrical impulses for the nervous system (Warren 8-9). For a diagrammatic representation of these anatomical structures, see Figure 4.

[3] Zahm, John Augustine. *Sound and Music*. Chicago: A. C. McLurg and Company, 1892. 152. Print.

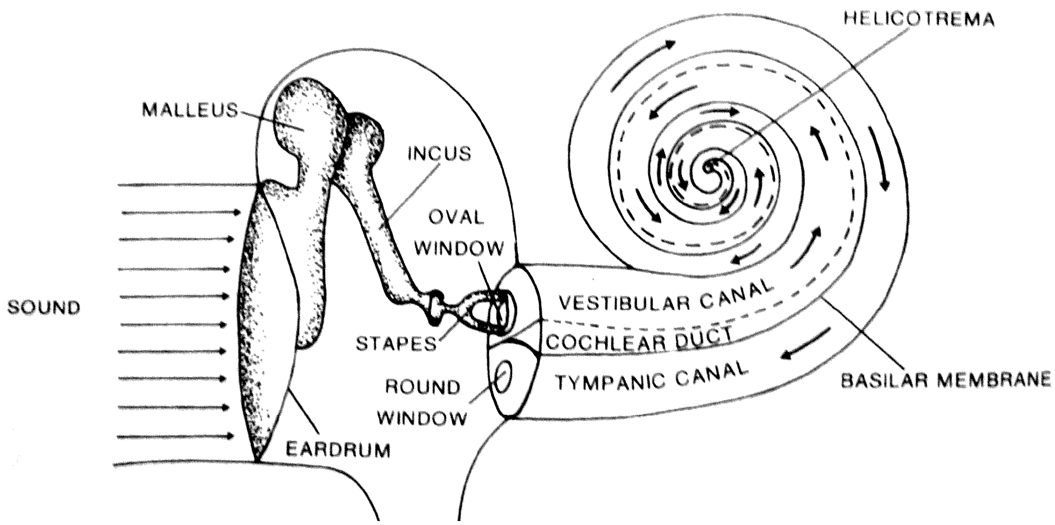

Figure 4. Sound Pathway in the Middle and Inner Ear[4]

The boundary between the tympanic canal and the cochlear duct is called the basilar membrane, and the resonant characteristics of this membrane account for the frequency range of human hearing. As James Beament of Cambridge University explains:

> Things can resonate over a small range of frequencies, but no object can resonate at any frequency from 16 Hz to 16 kHz, or so we might think… The basilar membrane is stiff at the end where vibration enters the tube, and resonates at high frequencies there. It continuously decreases in stiffness to the far end, where it is most floppy and resonates at very low frequencies. Some piece of the membrane resonates at any frequency in our hearing range (97).

The flexion of the basilar membrane triggers hair cells in the cochlear duct to fire nerve impulses which are required for perception. However, a given frequency causes resonance in a certain *segment* of the basilar membrane; the motion is not restricted to a single point location. This effect is shown in Figure 5, where the basilar membrane is represented as the horizontal line. When a fundamental frequency and its first harmonic are heard (as shown in Figure 5A) the resonant bands from each frequency overlap. In the overlapping region, the two frequencies reinforce each other at the fundamental frequency in much the same way as combination tones

[4] Warren, Richard. *Auditory Perception: A New Analysis and Synthesis*. Cambridge: Cambridge University Press, 1999, p 8.

are created (see **Section 2.02: Combination Tones**). Additionally, the longest portion of the basilar membrane that is resonating without interference always corresponds to the fundamental frequency, regardless of the harmonic count. This is the largest factor in hearing only one pitch for complex sounds despite the presence of multiple discrete tones.

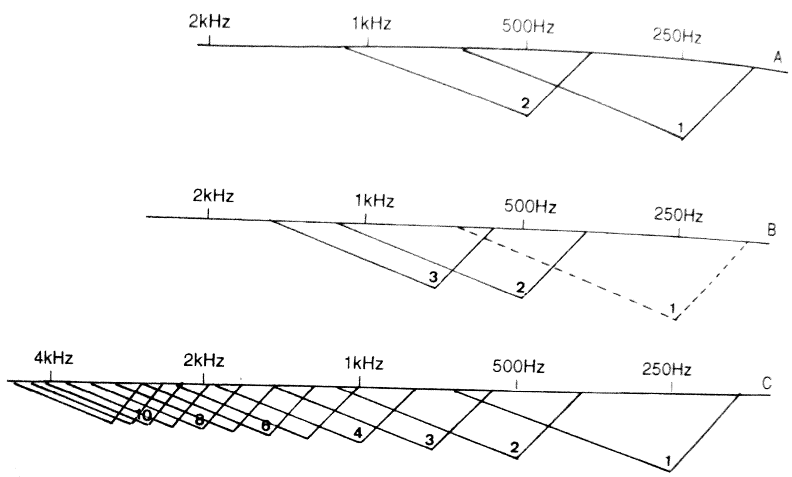

Figure 5. Vibrations of the Basilar Membrane to Pure Tone Harmonics[5]

Furthermore, with complex tones involving many overtones as in Figure 5C, a particular section of the basilar membrane tries to vibrate at multiple harmonic frequencies at the same time. At approximately the sixth overtone and above, the membrane cannot accurately represent this multi-frequency vibration and the generated nerve impulses degrade into noise (Beament 111). This corresponds well to the musical importance of the first six harmonics as discussed by John Zahm. The biological basis of complex tones forms the foundation for the understanding of all subsequent psychoacoustic phenomena.

[5] Beament, James. *How We Hear Music: The Relationship Between Music and the Hearing Mechanism*. Woodbridge: The Boydell Press, 2001, p 110.

2.02: COMBINATION TONES

Mathematically, two sinusoids of different frequencies will summate into a single amplitude-modulated signal similar to what is shown in Figure 6. The depicted signal is the result of the numerical sum of a 10 Hz sinusoid and an 11 Hz sinusoid and demonstrates a clear beating pattern once per second. The effect of Figure 6 can be generalized to apply to any two input tones: the amplitude of the summed signal will be the sum of the two input signals, and the frequency of the beating is equal to the frequency difference between the inputs. Neither signal's phase has an impact on the envelope of the final signal.

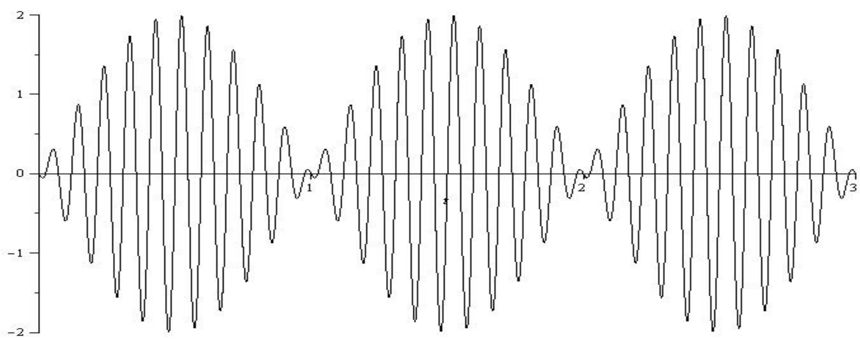

Figure 6. Sum of 10 Hz and 11 Hz Sinusoids.[6]

Applying this concept to sound waves, propagating sound waves do not sum together in air. However, simultaneous tones are still perceived simultaneously in the brain, including the beat frequencies, so the effect is the same even if the mechanism differs. Research has shown that when the beating frequency is less than about 20 Hz the pulses can be discerned individually by the ear (Rasch and Plomp 103). For higher frequency beats the ear "is no longer able to follow the rapid amplitude fluctuations individually (104)" and the beat degrades to a harsh raspy sensation termed roughness. Roughness lasts until the beating frequency is larger than the criti-

[6] Maple™ Command: plot(sin(10(2 Pi t)) + sin(11(2 Pi t)), t=0..3, -2..2, numpoints=100000)

cal band. At this point, any perceived sensation arising from the beating frequency disappears and the two input tones are independently resolved by the ear.

Beating is the simplest example of a combination tone – a perceived tone that is dependent on the frequency and amplitudes of the inputs but is not physically present in the acoustic signal (Rasch and Plomp 104). The most important combination tones are difference tones in which the frequency of the perceived tone is calculated by subtracting integer multiples of the two tones. If the two tones are of frequencies f and g and $f < g$, the first-order difference tone (beating) is $g - f$, the second-order difference tone is $2f - g$, and the third-order difference tone is $3f - 2g$ (105). These combination tones become increasingly fainter as the order increases and require increasingly higher sound pressure levels for the input tones to be heard. The summation tone $f + g$ is also possible but is incredibly difficult to detect because of masking by the lower-frequency input (Plomp 1123).

Of the combination tones, the first two difference tones have been the principal focus of psychoacoustic studies. In 1980, the German acoustics scientist Eberhard Zwicker compiled quantitative research on the first and second-order difference tones and developed two equations that roughly model the perceived amplitudes. Zwicker found that the sound level was highly dependent on the frequencies and the sound pressure levels of the two input signals. For the first-order difference tone he proposed Equation 1 as an appropriate model for the perceived loudness (Zwicker 1410).

$$L_{g-f} = L_g + L_f - 126 + 10\log_{10}[1 + (0.25g)^2] + 10\log_{10}\left[1 + \left({}^{0.5}/_{g}\right)^2\right]$$

Equation 1. Perceived Sound Level of First-Order Difference Tone

In this formula, f is the frequency of the lower tone, g is the frequency of the higher, and L (with appropriate subscripts for tone f, g, or the difference tone $g - f$) represents the sound pressure level. The second-order equation was substantially more complex and interested readers are encouraged to read his original article.

Determining the origin of combination tones is still elusive. Modern consensus is that the phenomenon is the result of the inner ear and is related to distortion product otoacoustic emissions (Ashihara 334). Otoacoustic emissions are sounds emitted from the inner ear that can be detected with a microphone probe that is inserted into the outer ear canal. The emissions are mostly far below the threshold of hearing so the sensitive microphones are necessary to even detect the signals (Zwicker and Fastl 35). While experiments have repeatedly linked distortion product otoacoustic emissions with the perception of combination tones, the origin of the emissions themselves is still unknown. Some researchers believe they could be the result of the amplification of the basilar membrane vibrations by the outer hair cells (Ashihara 334).

2.03: BINAURAL BEATS

Combination tones take on special characteristics when the two input tones are introduced separately to each ear, such as via headphones. In this case, the difference tone is referred to as a binaural beat. These beats are often generated with very low frequency differences between the two ears and can be used to demonstrate psychoacoustic effects. For instance, when the frequency difference is 0.5 Hz a "phantom source moves from one side to the other and back again each 2 seconds (Warren 35)". At the turn of the 20th century, this was one of the main arguments showing that interaural phase differences could be detected.

Binaural beats persist even when the frequency difference is increased so that the beating tempo increases. At a few beats per second, lateralization shifts (the traveling of the sound source from side to side) becomes difficult to detect and listeners report the sensation of the sound source being inside their cranium (35). The upper boundary of binaural beats is still disputed: some literature purports that they can be heard up to 3000 Hz (35), while other researchers cite an upper limit of less than 1000 Hz (Pratt 34).

Since binaural beats are created in the auditory cortex and brainstem (processing in the ear can be ruled out since each ear only hears half of the input stimuli), they are often used for evoking measurable brain potentials. In 2010, Pratt et al. conducted a detailed comparison of event-related potentials (ERPs, or the voltage differences that are measured in an EEG) induced by binaural beats and combination tones. The study involved creating eight stimuli patterns from three variables: beat type (acoustic or binaural), beat frequency (3 Hz or 6 Hz), and base frequency (250 Hz or 1000 Hz) (35).

These tones were played to eighteen subjects through headphones as in Figure 7. The results revealed interesting information both about the qualitative perception of the tones as well as the quantitative ERP measurements. Subjects reported that the acoustic beats sounded "somewhat more pronounced" than the binaural equivalent (37), and all eight stimuli could be detected by each participant. At the quantitative level, the brain response was maximized with acoustic beats over binaural beats, at a beating frequency of 3 Hz over 6 Hz, and with a base frequency of 250 Hz over 1000 Hz (41). These findings provide valuable guiding research for a sound design installation and contribute to our final plans that are discussed in **Chapter 4: Acoustic Implementation**. Overall, the results of the study indicated that the brain potentials were approximately similar for both binaural and monaural beats.

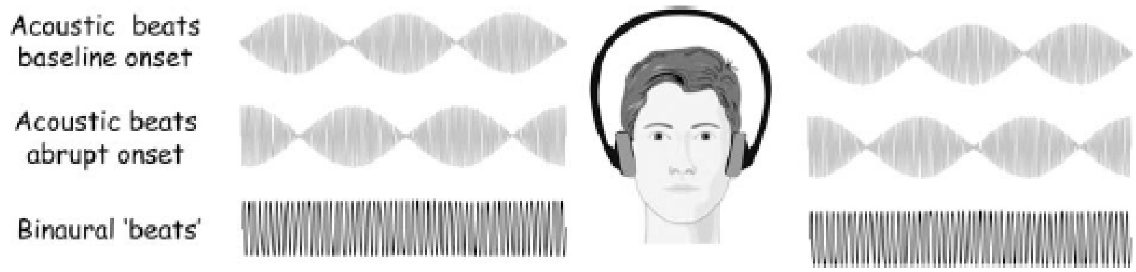

Figure 7. Pratt et al. Experimental Setup for Acoustic and Binaural Beats[7]

2.04: MISSING FUNDAMENTAL

Interestingly, experiments have shown that the perceived pitch of a complex tone is unchanged even if all energy is removed from the fundamental frequency. This phenomenon is called the missing fundamental, and shows that pitch perception does not rely solely on the spectral amplitudes, but on the harmonic content as well. In fact, the fundamental pitch can be perceived even if only two harmonics are heard, in which case this phenomenon reduces to a standard difference tone (Rasch and Plomp 98). Furthermore, the effect is not relegated to the laboratory; most electronics for voice recording or transmission have a limited bandwidth and partially cut out the fundamental frequencies of the human voice (Bendor and Wang 392).

Extensive experimentation was only done on the missing fundamental once tones could be generated precisely with computer software. This allowed researchers to create the complex tones they desired and strip all the energy from the fundamental frequencies. These sounds do not occur in nature, and natural selection cannot drive evolution without the presence of the stimulus. (It is possible that the fundamental frequency could be completely masked by another sound source, giving the effect of the missing fundamental. This would be rare, and auditory masking is an enormous topic beyond the scope of this research.) However, even though the

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[7] Pratt, Hillel, Arnold Starr, Henry Michalewski, Andrew Dimitrijevic, Naomi Bleich, and Nomi Mittelman. "A Comparison of Auditory Evoked Potentials to Acoustic Beats and to Binaural Beats." *Hearing Research*. 262. (2010): 34-44.

adaptive value of the missing fundamental effect is unknown, its presence in our evolutionary history is strongly supported.

Discussions about auditory perception can easily become discussions of culture, since many musical responses are learned by exposure to pre-established patterns. For instance, major key notes are often described as upbeat, while minor key notes are more melancholic. However, these are learned associations of Western culture and have no biological or evolutionary origin. To establish the missing fundamental and other psychoacoustic sensations as evolutionarily derived, it has to be demonstrated that they are not culturally-dependent or learned in any way. Infant studies are often used for this reason, since the babies are a *tabula rasa* and have not been exposed to cultural prejudices.

In humans, the perception of the missing fundamental seems to develop in early infancy. According to He and Trainor, previous behavioral studies have demonstrated the effect in seven month old children (7718). Experimentation with even younger infants is difficult because they are not sufficiently developed for behavioral studies; as such, He and Trainor devised an experiment that used electroencephalogram (EEG) recordings to gather quantitative data and relied on measuring the mismatch negativity response (MMN). As is further discussed in **Section 2.06**, MMN is an electrical potential difference seen on the EEG that occurs when the input the brain is expecting conflicts with the input that arrives. He and Trainor's trials consisted of playing "two complex tones with fundamentals, such that the pitch always increased from the first to the second tone. On occasional deviant trials, the harmonics of the second tone were all integer multiples of a low-pitched missing fundamental. "Thus, only if the missing fundamental was perceived should deviant trials elicit MMN" (7718). A graphical representation of this stimuli scheme is shown below in Figure 8.

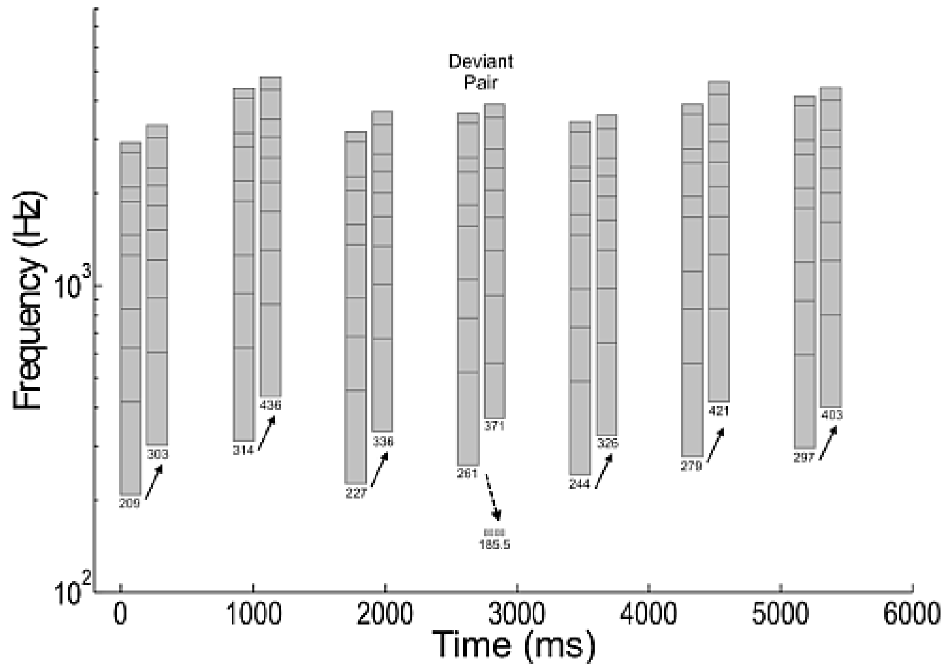

Figure 8. Sample Auditory Stimuli used by He and Trainor[8]

The researchers gathered participants that were three-, four-, or seven-months-old and recorded multiple EEG responses from each. The results showed a significant mismatch negativity response at the deviant pair for the four-month-old infants and older. This implies that the missing fundamental develops between three and four months of age in humans and that prior to this cutoff, hearing is frequency-based rather than pitch-based (He and Trainor 7720). The plots of the MMN for each of the three age groups are shown below in Figure 9. The missing fundamental is obvious for the two older groups on the left, and still undeveloped for the three-month-olds.

[8] He, Chao, and Laurel Trainor. "Finding the Pitch of the Missing Fundamental in Infants." *Journal of Neuroscience*. 29.24 (2009): 7720.

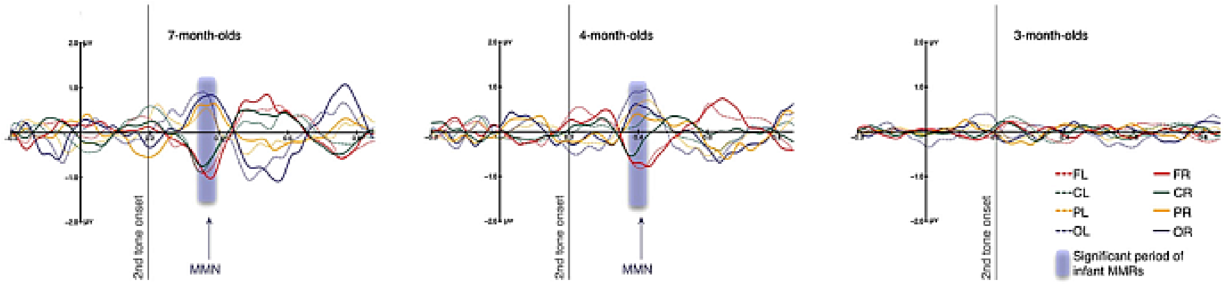

Figure 9. Infant MMN Response to Missing Fundamental[9]

The final conclusion made by He and Trainor is that pitch perception must occur in the auditory cortex, as has often been suspected. The brainstem is fully developed at birth, and while it is responsible for other mechanisms of hearing such as interaural localization, it cannot explain the lack of pitch perception in the three-month-old participants. This conclusion is further supported by human research showing poorer pitch discrimination with partial auditory cortex lesions (Tramo, Shah, and Braida 132), with greater loss of pitch perception if the damage was in the right auditory cortex or in the anterior auditory cortex (Zatorre 570). All of these findings collectively indicate that pitch perception is distinct from frequency perception and is a higher-level brain function.

The missing fundamental is also exhibited in other animals, which provides even more evidence that the ability has been passed from species to species down the evolutionary tree. In primates, Bendor and Wang have conducted extensive neuronal and cortical studies that show the missing fundamental is perceived in marmoset monkeys (396). The same effect has been shown in songbirds (Cynx and Shapiro 360) as well as cats (Heffner and Whitfield 919).

[9] He, Chao, and Laurel Trainor. "Finding the Pitch of the Missing Fundamental in Infants." *Journal of Neuroscience*. 29.24 (2009): 7771.

2.05: Applications of Psychoacoustics

Psychoacoustic effects are not purely experimental; they have been the foundation of several practical applications that have been marketed and commercialized. One area of notable interest is the reproduction of bass frequencies with small loudspeakers that do not have the size or the power to directly create these frequencies. Aesthetic and cost factors often drive speakers to become smaller and less robust, but this trades-off with low frequency performance.

One standard method of dealing with this challenge is to linearly amplify the bass range. This can easily be done with any simple digital signal processor (DSP), where the equalizer will add gain to the lower frequency bands. In theory, the small speaker's inability to fully drive these frequencies will negate the amplification and result in a properly scaled signal. The simplest drawback to this solution is inefficiency; the majority of power in the lower registers is being wasted. A more important concern is that the mechanical limits of the loudspeaker will limit the available stroke and induce distortion into the signal (Aarts, Larsen, and Schobben 59).

A more elegant solution is to "synthesize" bass register tones out of higher frequencies that the loud speaker can reproduce with more fidelity. There are two main advantages to this design scheme: there is a high radiated sound level to increase perceived loudness for a given power consumption, and less disturbance in neighboring areas because of higher absorption of higher frequencies (60). The creation of these low tones could use one of psychoacoustic phenomena discussed earlier, such as a missing fundamental, difference tone, or simple octave shifting. Regardless of the method, the loudness of resultant tone must be predictable so that the bass notes are neither overpowered nor underpowered.

An analysis of perceived loudness versus frequency results in the iconic Fletcher-Munson equal-loudness curves, which are pictured in Figure 10. These curves trace out the perceived loudness (in phons) of a sound wave at a particular frequency and sound pressure level (Butler 80). Key aspects of this graph are that the contours are densely packed in the lower frequency ranges and spread out in the speech range, and that the minimum SPL for audibility is much lower for speech range than low frequencies.

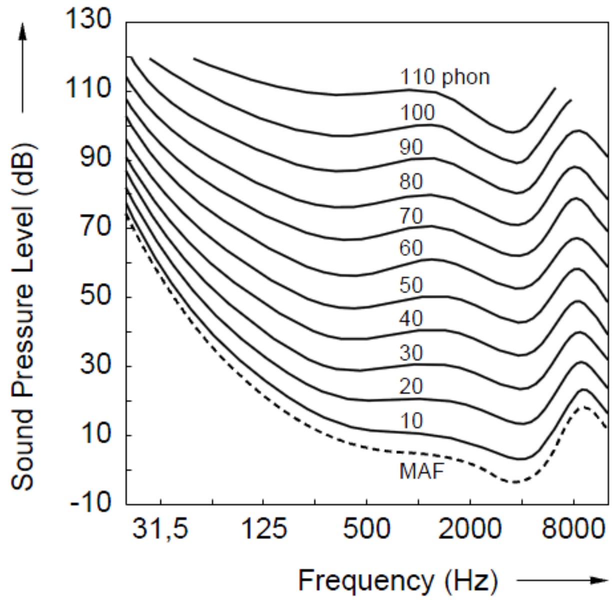

Figure 10. Fletcher-Munson Equal Loudness Curves[10]

These curves have a dramatic effect on the perception of low frequency tones that are created from multiple higher frequency tones. First, the perceived loudness of the bass is enhanced because ears naturally hears the higher tones composing it better than they would hear a pure bass note. Secondly, pure bass tones require a relatively small increase in SPL to yield a very large difference in perceived loudness, whereas a synthesized bass note will require a larger scaling of its higher frequency components to make the same loudness change (Aarts 62). This presents a challenge in algorithmically replacing low frequency notes with harmonic overtones since dynamic scaling would have to be incorporated (62).

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[10] Aarts, Ronald, Erik Larsen, and Daniel Schobben. "Improving Perceived Bass and Reconstruction of High Frequencies for Band Limited Signals." *Proceedings of First IEEE Benelux Workshop on Model Based Processing and Coding of Audio*. (2002): 59-71.

Based in large part on the theories outlined above for musical applications of bass notes, Waves Ltd. has patented a technology called MaxxBass, which "extends the apparent low range of loudspeakers by up to an octave and a half with no loss of efficiency, no increase in power input and no increase in size (Ben-Tzur and Collom 2)." This demonstrates how effectively psychoacoustic phenomena can be utilized to create perceptible auditory stimuli, and is another piece of supporting evidence for our sound design installation. MaxxBass relies on many of the same principles outlined by Aarts, Larsen, and Schobben, but additionally shows a diagram of the spectral composition of an input signal before and after processing (Figure 11).

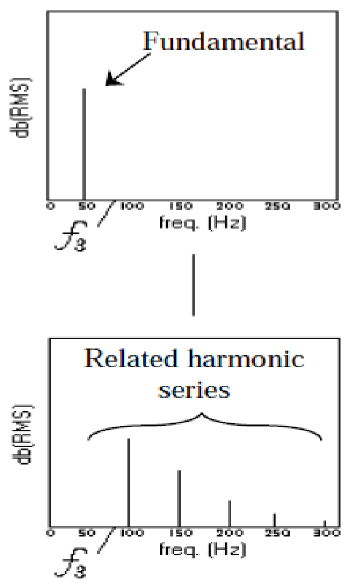

Figure 11. Block Diagram of MaxxBass Algorithm[11]

Here, the harmonics of the fundamental exponentially decay in amplitude and even the first harmonic is lower in amplitude than the desired bass note. This is to compensate for the increased hearing acuity at higher frequency ranges. Additionally, only a handful of harmonics are required to make a full-bodied bass note. As mentioned earlier, a missing fundamental tone can

[11]Ben-Tzur, Daniel, and Martin Colloms. "The Effect of MaxxBass Psychoacoustic Bass Enhancement System on Loudspeaker Design." MaxxBass, 1999. 20 Oct 2010. <http://www.maxx.com/objects/PDF/ MaxxBassAESPaper.pdf>.

be detected even with just two harmonics, and the MaxxBass algorithm uses five overtones. This indicates that the multichannel sound installation that we will propose should be well suited to create missing fundamental tones at normally sub-audible frequencies.

2.06: Brainwave Frequency Ranges

The human brain operates via a series of electrical impulses measurable by an electroencephalograph, or EEG. The full operation of the brain in its normal states can be measured and classified in five ranges, each with their own behavioral characteristics. These measured frequencies are relatively low, only reaching to about 60 Hz in the upper bound of brain activity (Snyder 118). Each frequency range has also been experimentally linked with "states" of mind and behaviors as summarized in Table 1 below.

Name	Range (Hz)	Function or Behavior
delta	<3	Deep Sleep
theta	4 - 7	Light Sleep & Dreaming
alpha	7 - 13	Relaxed consciousness
beta	13 - 20	Normal consciousness
gamma	>20	Sensory and cognitive processing

Table 1. Brainwave Frequency Ranges and Behavior

The first range is the delta range, and falls between 3 Hz and below. These extremely low frequencies of consciousness are associated with deep sleep. The second is known as the theta range, and falls between 4 to 7 Hz, and is again associated with sleep. However, the theta range is a more active state, seen in light sleep and dreaming. The third range is known as the alpha range, falls between 7 to 13 Hz, and is associated with a serene, calm consciousness or daydreaming state. The fourth is known as the beta range, and falls between 13-30 Hz, covering the typical alert human's brainwave frequency (First 31). The fifth and final range of brainwave activity, known as gamma, is seen during sensory processing, motor skill, and periods of heavy cognitive reasoning at above 20 Hz. This specific range of brainwave activity was shown to quickly follow acoustic stimuli over many tempos, supporting the theory that beat induction and auditory pattern recognition requires significant sensory reasoning and processing, which in turn produces brainwaves in the gamma range (Snyder 117-118).

2.07: Brainwave Entrainment

David First uses the unique term "sympathetic resonance" when describing an induced shift in brainwave activity as a result from nothing more than periodic acoustic stimulation. This biological response to a repetitive acoustic stimulus possesses the capability to modify the frequency at which brainwaves currently cycle in the brain.

Brainwave entrainment is a phenomenon linked with significant connections to the manipulation of the subject's consciousness because of the association of brainwave frequency ranges with mental states. The use of binaural beats has been shown to attract brainwave synchronization to the frequency of the difference in tones (First 31). For example, a 440 Hz tone played in the left ear combined with a 447 Hz tone played in the right ear would induce a 7 Hz frequency in the brain due to the difference tone. This 7 Hz frequency would fall into the alpha range of brainwave activity, which is associated with a meditative and relaxed consciousness. This shift in consciousness is evoked by nothing more than an application of a binaural beat targeted to produce a very low frequency overlap. This method of consciousness manipulation has been shown to specifically be useful in the areas of "stress reduction, pain control, and the improvement of concentration and information retention" (31). First also investigates the possible implications of being exposed to what he calls the constant “Hum of The Earth” (32). He explains this “Schumann Resonance” is a large scale, constant, acoustic resonance occurring in the Earth’s ionosphere as a result from the acoustic pressure impulses from the constant lightning strikes around the world. Studies show the resonating frequencies would range from 8 Hz to around 45 Hz, curiously all within the range of human brainwave activity (35 – 36).

A study conducted by Will, Udo, and Berg demonstrated a unique response from entrainment-oriented acoustic stimuli in the 14-44 Hz (beta and gamma) range over a group of ten subjects. An EEG was used to monitor brainwave activity during an acoustic stimulus of a specific low frequency and the results can be seen in Figure 12. This strong response is noted that it is “different from those in the lower frequency ranges” (Will, Udo, and Berg 58). However, the authors conclude the absolute strongest response occurs at 2 Hz and corresponds correctly with previous frequencies found in repetitive sensorimotor actions. Finally, they cite a needed synchronization for “neurophysiological processes” to link a timing component “between rhythmic sensory input and motor output” (59).

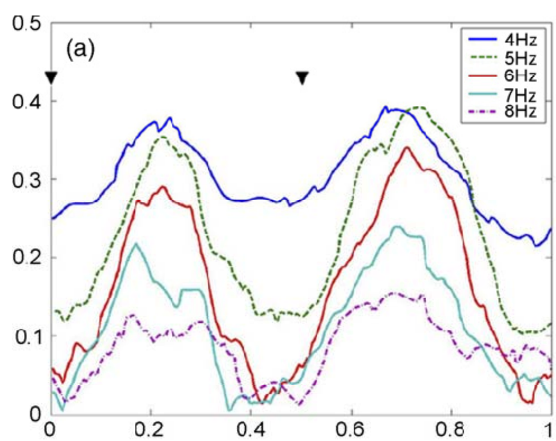

Figure 12. Young Adult Brainwave Activity during Repetitive Acoustic Stimuli[12]

[12] Will, Udo, and Eric Berg. "Brain Wave Synchronization and Entrainment to Periodic Acoustic Stimuli." *Neuroscience Letters*. 424. (2007): 58.

The acoustic frequencies used during the study consisted of both traditional drum beats as well as non-descript clicks and pulses, and resulting measurements revealed both stimuli had similar entrainment capabilities. This reduces the entrainment action to a biological level, as culturally influenced modern drum beats evoked responses no different than any other repetitive, audible pulse or frequency.

Conversely, brainwave entrainment has also been shown to be present in a much higher frequency band well above the range of human hearing. The process of using binaural and simple beats to entrain brainwave activity has previously been limited to applying acoustic stimuli with frequencies falling within the range of the human brainwaves (1 – 60 Hz; relatively low frequencies). William Tyler and others from Arizona State University conducted a study focusing on low-intensity, low-frequency ultrasound (LILFU) as a non-intrusive means to induce brain activity. The experiments were conducted with both living organisms and isolated brain tissues, and results were similar. LILFU frequency falls between 0.60 – 0.70 MHz, far outside the upper limit of the human brainwave frequency range. Precise application of these acoustic based frequencies was shown to stimulate electrical reaction from neurons by "activating voltage-gated sodium channels," as well as "voltage-gated calcium channels" (Tyler 1). Previous studies have focused on High-Intensity and High-Frequency Ultrasound which has been shown to cause nerve damage. However, LILFU showed no negative degenerative actions on neuron membrane integrity after 8 minute periodic exposure for up to 48 hour timeframes (3). LILFU was shown to cause major neuron activation, including the ability to affect neurons related to chemical production systems that signal:

> synaptic transmission, neuronal growth/survival [46,47], cell fate specification, tissue patterning, axon guidance in the nervous system [48], and angiogenesis in the brain [49]. Moreover, VEGF [49,50], TGF-b [51,52], and bFGF [46] are neuroprotective against hypoxic-ischemic injury and neurodegeneration (7).

Tyler's study concluded LILFU can be used to non-invasively stimulate central nervous system neurons in living tissues while the subject remains alive. The ideal transfer of LILFU through the skull and its non-degenerative behavior upon neuron membranes supports the possibility for LILFU to be used for deep-brain stimulation without any invasive surgery (8).

2.08: Mismatch Negativity (MMN) Response

The mismatch negativity response is an electrical potential difference seen on the EEG that occurs when the input the brain is expecting conflicts with the input that arrives. This occurs frequently when the brain has been entrained to expect a certain pattern or type of stimuli that is suddenly omitted. Rather than adapt instantly to the loss of the pattern, the brain continues to exhibit synchronous brainwave behavior as if the stimuli continued, with the MMN defined as the size of these deviant spikes of brainwaves.

István Winkler, a Hungarian psychologist, demonstrated the ability for even newborn infants to detect and entrain to the beat in modern day music by revealing an MMN response using nothing but basic acoustic stimuli similar to samples used in Will, Udo, and Berg's experiment. The repetitive beat found in music stems mostly from a traditional drum based rhythm track, so a simple 4/4 basic quarter note MIDI tone drum beat was created to use for the stimulus. The choice of instrument is unimportant as shown by Will, Udo, and Berg; any repetitive acoustic stimulus will produce the same entrainment response. Traditional drum tracks were chosen because the standard binary rhythmic structure they contain allows for strategic removal of specific beats (Winkler 5). The structure of the beats (both omissions and sounds) is shown below in Figure 13.

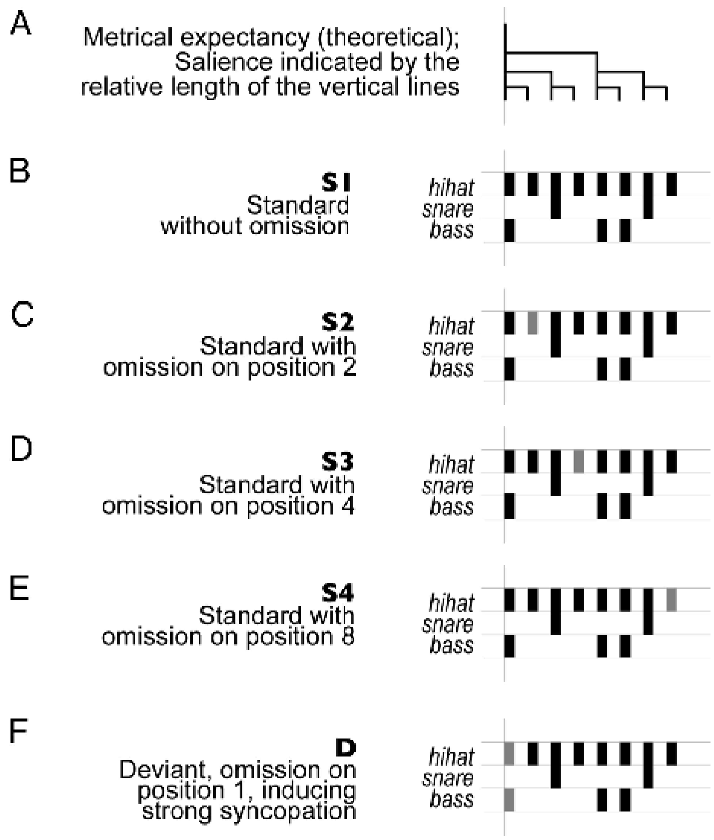

Figure 13. Structure of MIDI Drum Beats[13]

It is noted that the omissions "do not break the rhythm when presented" to the subjects, because introducing a different rhythm would cause a new instance of beat induction and entrainment to occur, skewing the intermittent brainwave activity instead of isolating a clear MMN response (Winkler 1). The following figure illustrates the brainwave activity observed when an omitted beat was encountered.

[13] Winkler, István. "Newborn infants detect the beat in music." Institute for Psychology, Hungarian Academy of Sciences (2008) 2.

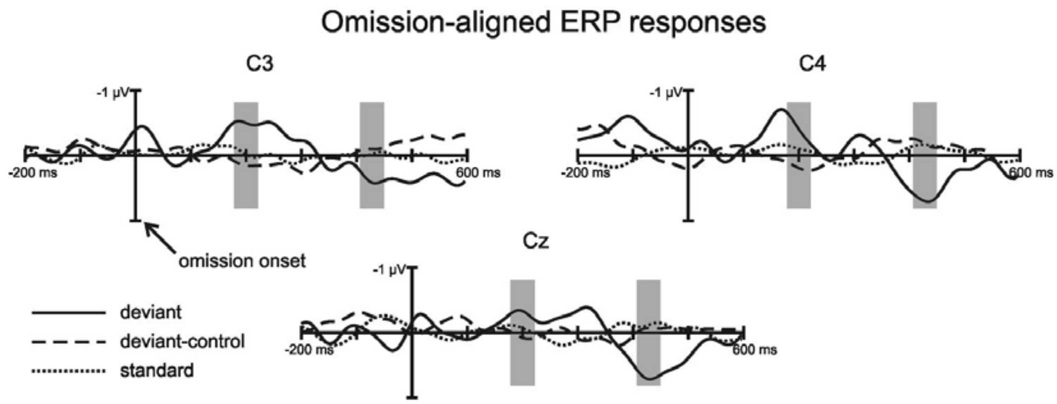

Figure 14. MMN Response Highlighted in Infant Brainwave Activity[14]

2.09: Beat Induction

During exposure to a periodic acoustic stimulus, the human brain demonstrates an uncanny auditory processing ability to quickly learn, recognize, and accurately predict patterns in the sample. One of the most obvious derivatives of this tendency is physically visible: when you find yourself subconsciously tapping your foot to the beat in music, your brain has become induced with the beat through a process of attunement, and is now accurately predicting the time periods between additional beats in the sample (Drake 254). A binary breakdown of this processing ability allows even the most complicated pieces of music to be separated into successive layers of patterns and classified correctly by our brain in seemingly real-time (Drake 252-253). Deviance from an expected pattern results in a specific negative brainwave activity known as the previously discussed mismatch negativity response.

The words 'beat induction' have both rhythmic and mathematical roots. According to the dictionary definition, to induce something is to 'put into formal possession;' in this case, a listener's subconscious attention is inherently drawn to repetitive acoustic stimuli and eventually in-

[14] Winkler, István. "Newborn infants detect the beat in music." Institute for Psychology, Hungarian Academy of Sciences (2008) 2.

duced into analyzing and predicting further occurrences of the beat. A beat is traditionally limited to simple audible pulses of acoustic stimuli in music, but in this case can refer to any occurrence of periodic sounds. Whether the stimulus is a single sine wave or a recurring verse-to-chorus structure is unimportant; both will cause some measure of induction when applied to a human listener's ears (Wunderlich 1527). Beat induction abilities and preferences vary between persons (as with any other subjective characteristics) and some may recognize and adapt to complex patterns and frequencies easier than others (Drake 254).

Each individual person has a natural referent period, or time period between repetitions that they favor. When someone is asked to begin tapping their finger spontaneously without listening to an audible rhythm, they will most likely gravitate towards the frequency of their referent period. Similar to a referent period, a referent level refers to the amount of stimulus required to catch the listener's attention and coax their brain to begin accurately expecting additional pulses. When exposed to acoustic stimuli with a repetitive period similar to one's referent period and with a degree of repetitiveness complementary to one's referent level, a person can effortlessly pick up the beat seemingly instantly. This process of the brain's attention rapidly adapting to a given frequency is known as attunement, the same term given to the procedure to tune any oscillator to match a periodic frequency (254).

The aforementioned descriptors of a referent period and level encapsulate only a single instance of repetition; oftentimes a hierarchy and multiple layers of repetition are present, such as in any traditional piece of music. The "Dynamic Attending Theory" summarizes the human brain's ability to apply this basic attunement to all of the patterns present in the environment as they are occurring, halting, and varying (this type of changing data is called dynamic), while still classifying each additional *onset*, or beginning of a note or beat, into its appropriate sequence into the current hierarchy. This hierarchy of expected sequences is known as an expectancy scheme, and is the set of all single time level repetitive frequencies that have been noticed by the human brain (255).

Carolyn Drake from the University René Descartes in France conducted a significant beat induction study over a group of musicians and non-musicians with various ages. The subjects were asked to provide a sample of taps to various rhythmic and non-rhythmic acoustic stimuli to quantify their inherent referent periods and levels against their age and musical ability. The same subjects were then asked to follow a given frequency by similarly tapping on the electronic pad in an effort to quantify data about their attunement process against their age and musical ability. Six year olds, eight year olds, ten year olds, and adults (both musically-inclined and not) comprised the eight sample groups (262). The results of the referent period and level experiment are shown in the scatter plots below.

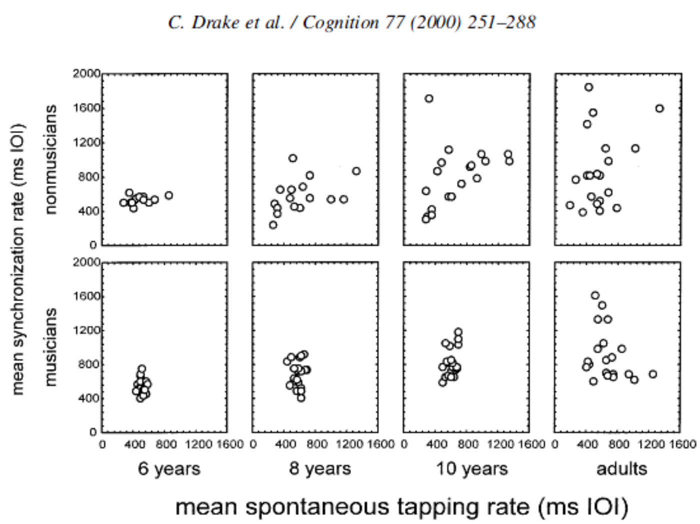

Figure 15. Spontaneous Tapping Rates[15]

[15] Drake, Carolyn, Mari Jones, and Clarisse Baruch. "The Development of Rhytmic Attending in Auditory Sequences." Cognition. 77. (2000): 275.

The horizontal axis is the mean spontaneous tapping rate, or the average frequency of each subject's unprovoked-tapping sample data. The vertical axis is the mean synchronization rate, or the average frequency of each subject's time needed to attune and match the frequency of a given periodic acoustic stimuli. Drake's conclusions show that over time, inherent referent periods appear to slow as well as the time required for the brain to attune to a given acoustic frequency, indicating the degeneration of beat induction abilities due to age. However, the musically inclined population clearly retained abilities, indicating that constant stimulation of the necessary acoustic functions such as beat induction reinforces their preservation.

Modern technology and computer software has brought signal processing and creation to levels far outside the reach of hand-creation, because in almost all cases when it comes to complex numerical calculations, our own brain can be out-performed with ease. Computers can determine the frequency, amplitude, and phase of a sine wave to a further degree of accuracy than a human ever could. However, even with their extreme speed and precision, computers lack the fundamental high level acoustic processing abilities that we may take for granted or not notice at all.

The concept of the missing fundamental is a sub-conscious recognition of a common interval between multiple harmonics as an audible tone. Humans perceive the overlapping phases of the harmonics as simply a tone. Everyone perceives this pitch, albeit at a unique loudness and timbre. Computer software and hardware, however, are limited to recognizing only the signals of the harmonics. Processing the values of each, recognizing a common interval, and creating the implied tone requires a large amount of computation. To artificially detect a missing fundamental, the computations and evaluation algorithms would need to run constantly over the sample, severely increasing computational requirements. Humans process this information subconsciously, and don't even consciously notice the effort of finding the common tone. A similar situation is encountered when comparing artificial beat induction with biological beat induction; the computational requirements quickly reach a point where the human's biological recognition far outperforms even the most advanced computers.

A study at Stanford University's Department of Computer Science demonstrated a fairly accurate method for creating an artificial system to mimic a biological beat induction style behavior. The system was software based and – in contrast to our biological auditory system - was not designed to process data in real-time. The software would sample a digital audio file, perform various transforms and analysis to create a template of probable beats, and examine the results once more to finally classify them as a beat or disregard them (Dhangwatnotai, Shinde, and Vongmasa 3). The software's analysis stages are shown below in Figure 16.

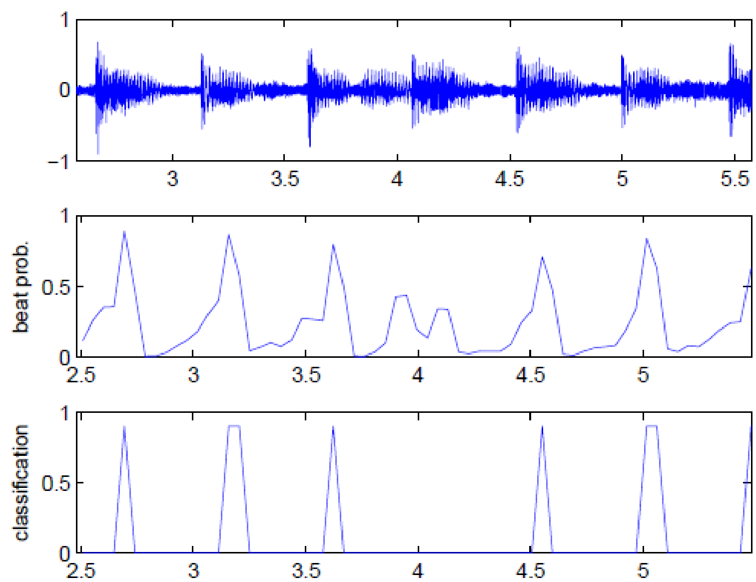

Figure 16. Stanford's Artificial Beat Induction Evaluation Procedure[16]

[16] Dhangwatnotai, Peerapong, Rajendra Shinde, and Pawin Vongmasa. "Beat Induction and Rhythm Recognition." Stanford University Department of Computer Science. 15 December 2006. <http://www.stanford.edu/class/cs229/proj2006/ DhangwatnotaiShindeVongmasa-BeatInduction.pdf>. 3.

Finally, an algorithm was designed to examine the interval between the accepted beats and average the closest, most occurring intervals in an effort to accurately capture the beat frequency of the sample. The first 75% of the data was used for learning the beat, and the last 25% of the sample was used for testing the concluded finding (3). After 20 pieces of music, and despite the computational power of the computer on which the software ran, the accuracy of the system was found to only be around 85%, far worse than human ability (5). It is to be noted that this complex system was designed to only process a given finite, somewhat simple auditory stimulus with no implementation of any expectancy scheme for overlapping beats; one of the *lowest* complexity auditory stimulus the human brain is capable of processing at a subconscious level.

2.10: Psychological Effects of Background Sound

As shown in the above sections, certain aural stimuli can have a demonstrable effect on brainwaves and brain activity. Beyond this psychoacoustic research, a vast amount of resources have been dedicated to investigating the effect of background sound and music on psychology and behavior. This research can be viewed as an extension of the purely biological brain studies to see the manner in which sound can create measurable changes in listeners' actions or attitudes. The most iconic company that has pursued this research has been Muzak. Specializing in functional music that is made to be "heard, but not listened to (Radano 450)," Muzak was so pervasive at its peak that it was synonymous with all types of this environmental sound, even though Muzak was only one company of many that specialized in this area.

Despite the scorn that sometimes accompanies mentions of the company, there are substantial scientific underpinnings for Muzak's methodology. The company's promotional literature portrays Muzak as "psychologically active, sonic accompaniment, carefully designed to remain below the threshold of common attention (450)." The purported effects included boosting employee morale and productivity or increasing customers' subconscious desire to purchase goods. Far from being restricted to in-house research, many scholarly articles support these claims to some degree. Their conclusions can easily be extrapolated from simple atmospheric music and can be applied to broader categories of background sound such as the currently proposed installation.

After an intensive study of environmental background music in retail stores, Jean-Charles Chebat et al. determined that the level of cognitive response to background music is dependent on the fit, familiarity, and tempo of the stimuli (120). The fit of the music to the atmosphere and its familiarity to the listener are difficult to quantify or control in an experiment, but the effect of tempo was clear in the study's results: slower tempos enhanced alpha brainwaves and increased cognitive activity, while higher tempos did not fit with the commercial context and hindered cognition. This is a strong example of brain entrainment's application to the real world; the soothing tempos of the stimuli can coax the brain into attending to the salesperson's sales pitch, but when the tempo becomes too accentuated attention is drawn to the sound source itself and the effect on sales is deleterious (121).

While tempo can be easily quantified, the fit of the music to the environment and its familiarity to the listener are more abstract concepts. Nevertheless, Chebat concluded that "what really matters in store music is its evocative power – memories related to the music (121)." If the incoming sound and the customers' other impressions of the retail environment do not match well, the impression of dissonance can severely hamper the sales pitch. On the other hand, if there is good congruence between the two, statistical evidence shows an increased propensity for sales. The high dependence on personal response prevents environmental music from being an assured booster for sales, but the evidence does conclude that sound has a distinct effect on shoppers. This is independently verified by many other research studies such as Garlin and Owen (2007).

Casino environments are another location where the levels of the subjects' personal responses to the background sounds determine the magnitude of the cognitive response. Behavioral effects from music and other acoustic stimuli are shown to be targeted for profit in the field of gambling, specifically in how the environment is designed to encourage listeners to continue spending. Griffiths and Parke of Nottingham Trent University investigated the implications of the typical gambling environment's acoustic atmosphere insofar as affecting guests' behavior. Previously, research from a university cafeteria centered acoustic study had suggested a correlation between emotion, and an accepted financial range; pop and classical music led to an atmosphere of elegance, optimism, high class, and confidence, finally demonstrating practical financial gain in increasing the maximum prices students were willing to pay for food after exposure (Griffiths). Conversely, supermarkets demonstrated that music with higher audible levels encouraged nothing more than an increased desire to exit the environment in a timelier manner.

These subconscious reactions to acoustic stimuli clearly demonstrate emotional and behavioral connections and have provided the foundation for the specific design of slot machine acoustics. The emotional vulnerabilities found in human audio processing provide the framework for a sound installation environment that maximizes profit for the casino owners by encouraging spending behaviors. The constant reinforcement and highlighting of winning scenario sounds, while downplaying and even ignoring sounds of losing scenarios, creates a misleading appearance of success. Machines that win draw extreme attention to the player and the event by providing loud and prolonged acoustic stimuli, creating a strategically positive environment.

Emotional attachments to familiar compositions, cinematic scores, or video game soundtracks are used to distract and entice the user into falling into sense of security with the machine. It is surmised that this immediate acoustic familiarity solidifies an instant subconscious emotional connection with the machine, thereby increasing the chances the listener will continue to remain with the machine and spend money (Griffiths).

Many times people retain a strong set of memories or other emotional attachment to certain songs. By providing request-based sources for these musical tracks, capitalists try to constantly provide subjects with the emotional connection and satisfaction they desire, knowing their resulting optimistic, excited emotional state will encroach on their rational judgment. This impaired behavioral condition is one of the best opportunities for exploitation, as it encourages purchases or other decisions to be made while the subject's logical reasoning skills are lowered (Griffiths).

The behavioral implications of psychoacoustic stimuli are one of the highest and most derived applications of our biological ability to process sound waves. The scientific underpinning of these behavioral responses is again the mismatch negativity (MMN) response; this demonstrates the cohesion between the roots of the psychoacoustic effects discussed earlier and behavioral responses to sound stimuli. Speech, even in its most basic forms, is arguably the most advanced sound stimuli the human ear can be exposed to, yet it is still governed by the fundamental brainwave reaction of MMN as investigated by Shtyrov. The department of philosophy in Helsinki demonstrated the advanced evolutionary steps that the brain has taken to facilitate speech processing. By measuring MMN responses when given a deviant sound sample after experiencing a repetitive speech sound component, the hemispherical distribution of the speech synthesis functions was studied. As increasing levels of background noise were combined with the speech sounds, almost all subjects' data showed a distinct shift in audio processing from the left to right hemispheres (Shtyrov 103).

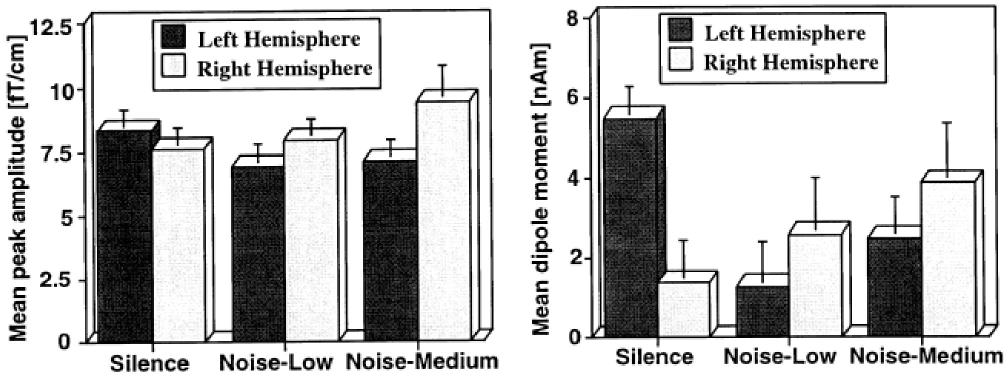

Figure 17. Hemisphere Distribution of Speech & Noise[17]

Another example of MMN's prevalence in behavioral studies was found by Gianna Cassidy and Raymond MacDonald of Glasgow Caledonian University. They conducted a study on the effect of background music or noise on the task performance of introverts compared to extraverts. The results showed that high arousal background music was less conducive to task performance than low arousal sounds; the authors' hypothesis for this phenomenon is that high arousal sounds are "more unpredictable in structure, timbre, and message than the [low arousal] music (531)." This is an exemplary example of the mismatched negativity response, where the encountered deviances interrupt the brain patterns and distract the user from the task at hand. The low arousal sounds that had predictable structures and soothing rhythms instead enhanced the productivity of both personality groups (531).

[17] Shtyrov, Yury, Teija Kujala, Jyrki Ahveninen, Mari Tervaniemi, Paavo Alku, Risto Ilmoniemi, and Risto Näätänen. "Background Acoustic Noise and the Hemispheric Lateralization of Speech Processing in the Human Brain: Magnetic Mismatch Negativity Study." *Neuroscience Letters*. 251 (1998): 143.

Chapter 3: The Theory

The existence of psychoacoustic effects has been well demonstrated in literature, but what is the origin of these phenomena? What caused them to come into existence and what purpose have they served over mankind's evolutionary lifetime? According to some theorists, the answer lies in indomitable force of evolution (Mithen 11). At the most primal level, our hearing adaptations have enhanced the survivability of the species, and continually refined versions of the auditory system are genetically inherited by future generations.

As demonstrated in most species, auditory sensitivity plays a significant role in surviving. In predators, spatial localization allows an animal to locate and track prey that may be out of sight. Studies have shown that deaf predators are less effective at hunting; natural selection eliminates the less genetically fit from a society. Conversely, an acute sense of hearing allows prey to hear potential predators and provokes a fight or flight response. These two facets to the sense of hearing are exhibited in all species to some degree, even including humans. While we no longer rely on a sense of hearing to secure a food source, we still experience an involuntary surge of adrenaline from loud, abrupt noises.

The core survival sense relies mainly on determining sound intensity and location, but does not account for the complex rhythm and pitch detection abilities that are utilized in our everyday auditory scenes. These are higher level functions that slowly developed to meet the needs of the human condition. For example, James Beament speculated that the earliest form of rhythmic understanding was a result of long distance running. The increased stamina required for long distance running was yet another adaptation that made mankind better suited to survive, and any apparel or ornamentation worn would slap rhythmically in time with their stride (92).

As running became a daily activity, the increased exposure to these repetitive auditory stimuli taught the earliest form of what is modernly called beat induction.

Similarly, pitch perception developed and evolved to give the human species a heightened chance of survival. As early hominids began living together in communities, communication became increasingly important for organized hunting. Long before formal languages developed, information was conveyed via differences in pitch in timbre; just location and intensity were no longer adequate. Steven Mithen from the University of Reading suggests that this "proto-musical language" was in fact also the origin of musicality (5). At this point in evolutionary history, humans could experience the three foundations of modern music (rhythm, pitch, and timbre), and had even begun to build primitive instruments (Beament 92). Furthermore, over millions of years, the biological hearing mechanism has been tuned to enjoy specific tone intervals, eventually defining the Western scale among many others. The mechanics of this involve the resonant frequencies of the basilar membrane and were explained more fully in **Section 2.01: Complex Tones**.

Species further down the evolutionary tree provide more evidence to support these theories. In particular, primates are noted for their genetic similarity to humans and share an evolutionary history that includes the development process for advanced auditory functions. Bendor and Wang showed through electroencephalogram measurements that marmoset monkeys sense pitch (396). This ability is not crucial for survival in terms of securing food, but instead supports the development of communication within their community. Pitch is used to encode emotion, mating calls, distress, and other signals with a higher degree of precision than volume could. A similar ability is also seen in the songbirds mentioned in **Section 2.04: Missing Fundamental**, which require pitch as part of their mating rituals.

An argument could be made that psychoacoustic effects are learned from the environment rather than evolutionarily derived; however, studies show that infants exhibit these abilities long before exposure to formulaic cultural influences. At a biological level, infants have demonstrated complex pitch perception (He and Trainor 7718), as well as beat induction and the resulting mismatched-negativity response (Winkler 3). Infants are regarded as blank slates, culturally innocent specimens that provide a basic biological engine to study; these studies reveal that music's underpinning psychoacoustic effects are innate.

While musical preferences and emotional attachments are certainly learned by personal experience, Sandra Trehub conducted founding experiments showing a musical predisposition in infants. Their perception of complex sounds is more than the sum of the sense of pitch and rhythm; rather, infants can recognize an emotional value in musical sequences (8). This is implicitly understood by mothers, who accentuate pitch and rhythm in a "sing-song" manner when communicating. Trehub's research indicates that these early musical sequences facilitate their use as primitive speech signals and are effective long before the infant learns a more formal language. Young babies are truly predisposed to be receptive to musicality.

These collective observations lead to the motivation for this sound design project. Our research has shown that our hearing system was originally necessary to ensure survival and has evolved into an apparatus with extreme abilities of discrimination. This phenomenon can also be seen in a multitude of species that still require the sense of hearing to hunt and stay alive. These animals have their hearing ability continually reinforced by natural selection, and therefore have an even more acute sense than humans. As a simple example, feral cats can hear frequencies far beyond the range of human hearing and have incomparable spatial localization abilities; these heightened senses are necessary for their continued hunting success. In contrast, human intelligence has supplanted our sense of hearing as the critical method of securing food. Correspondingly, without the force of natural selection, our senses have stagnated and no longer seem to be developing. As Steven Pinker summarized, "music is auditory cheesecake," alluding to the fact that the usage of our senses is shifting to pleasure rather than survival.

When muscles have potential strength but are not exercised sufficiently, they become progressively weaker and ultimately atrophy into an unusable state. Analogously, humans are born with much finer perception of frequency, timing, and timbre (Trehub 3) than are required for speech or music. This enhanced sensory ability decays over time from lack of use, ultimately restricting what the adult is capable of hearing. As another example, young children demonstrate superior beat induction skills over adults (Drake 276). Our Interactive Qualifying Project aims to prevent the atrophy of innate psychoacoustic abilities by exercising and reinforcing the listeners' perceptual skills with specific auditory stimuli.

Increased exposure to these fringe stimuli has been shown in a clinical setting to awaken previously dormant human auditory processing abilities. Over the span of a lifetime, Drake's beat induction experiments show that musicians retain higher rhythmic proficiency than non-musicians; the continual exposure and practice to beats and metrics has reinforced a higher ability level than those who choose not to perform music (See Figure 15). While this experiment showed that sensory exercise is important over a timeframe of many years, research on the upper limit of perception for the missing fundamental showed that auditory performance could actually be increased in short periods of time. Participants who were not able to initially hear a missing fundamental tone at a given frequency eventually could detect the same tone after mere hours of exposure. This process was repeated with continual advancement in the upper range of perception with prolonged exposure.

These findings show that humans have untapped auditory ability beyond what is initially visible, and this potential can be accessed via listening to crafted acoustic stimuli, and the subject can be consciously aware of the improvement. This project selects four of the main psychoacoustic phenomena researched – difference tones, beat induction, brain entrainment, and mismatched negativity – and aims to increase listeners' conscious sensitivity to each by exposing them to specially designed stimuli. Ultimately, auditory stimulation encourages auditory sensitivity and may help avert the sensory atrophy that occurs by neglect.

Chapter 4: Acoustic Implementation

The purpose of this sound design is to target and explore psychoacoustic responses of the human brain, specifically beat induction, brainwave entrainment, mismatch negativity response, and missing fundamental. To accomplish this, three custom auditory stimuli tracks were created and sequenced, drawing off of the research conducted above from the psychoacoustic and hearing journals. Whereas most clinical experiments are monaural or binaural, this sound design utilizes two independent 2.1 stereo systems. By efficiently leveraging the crossover frequency of each sound system, this architecture allows up to six independent audio channels. Furthermore, the physical installations can be maneuvered around the room to distribute the channels around the listener providing a more immersive environment.

In this sound design, all auditory tracks were designed to reflect the findings of the background research. One of the common themes in the creation of the stimuli was that of the psychological effects of background sound, as discussed in **Section 2.10**. The overarching concept of this research was that behavior and emotions were most influenced when the auditory stimuli were not actively focused on. The generated stimuli were designed to be below the threshold of consciousness where they could be considered distracting and draw attention. This was accomplished by using low tempos, familiar musical elements merged with unfamiliar stimuli, and low volumes. This draws heavily on the research in the field of background sound perception performed by Chebat, Griffiths, and Radano.

The second common theme considered during auditory stimuli generation was to evoke a synchronized brainwave response from the listeners in the alpha range. In all generated samples that featured difference tones or a missing fundamental, the algorithms were designed so that the perceived pitch was 10 Hz. According to the brainwave frequency research by David First discussed in **Section 2.07**, 10 Hz falls directly in the middle of the alpha range; this range is associated with relaxed consciousness. This level of alertness is ideal for remaining in a state where the psychoacoustic effects targeted in this project remain subconscious. Additionally, if listeners are shifted into a relaxed mental state, they are less likely to question or reject the presence of the physical sound installations.

The overall auditory stimuli consists of three approximately fifteen minute tracks that are randomly interspersed with twenty minute periods of apparently silent interludes. Using these building blocks, a multi-hour synchronized playlist was created. As illustrated in Table 2, the two installations will play complementary tracks, but the sequence appears random in the order of the specific tracks and interludes. By repetition, the length of the audio experience can be extended to last for hours, days, or even weeks at the artist's discretion.

Installation 1	**Installation 2**
Track 1 - "Beat Induction"	Track 1 - "Beat Induction"
Interlude - Silence	Interlude - Silence
Track 2 - "Bars and Ambiance"	Track 2 - "Bars and Ambiance"
Interlude - Silence	Interlude - Silence
Track 3 - "Sweeps and Scales"	Track 3 - "Sweeps and Scales"
Interlude - High Frequency	Interlude - High Frequency
Track 2 - "Bars and Ambiance"	Track 2 - "Bars and Ambiance
Track 3 - "Sweeps and Scales"	Track 3 - "Sweeps and Scales"
Interlude - High Frequency	Interlude - High Frequency
(randomly continues)	(randomly continues)

Table 2. Sample Synchronized Playlist Structure

The first track - casually named "Beat Induction" - features a complicated 4/4 beat pattern that builds to completion over six minutes, maintains the entire beat for two minutes, and gradually decays in the final six minutes. This track was designed to heavily stress the listener's beat induction ability and cause regular MMN responses; the brain attempts to find rhythmic patterns in the sounds, but is continually thwarted by the random omission of critical expected onsets. At every variance from a recognized pattern - whether the overall beat pattern or merely a fragment - an MMN response will be triggered and force the brain to reevaluate the auditory environment. Ultimately, the goal of extreme beat induction provocation via MMN is to enhance people's ability to find and *consciously* recognize subtle patterns in auditory stimuli. Like the saying "practice makes perfect," the more times the brain tries to find a beat, the more honed the ability will become.

The original beat structure was a looped hip hop style beat supplied by Apple's GarageBand software. The build-up was accomplished by systematically introducing increasing numbers of onsets per measure over time. Towards the beginning of the track, very few onsets are present, which makes it difficult or impossible for a listener to isolate a pattern or beat, even though all perceived sounds do align with the original pattern. Gradually, the increasing number of onsets assists the listener in finding pattern fragments. This was implemented by manually removing onsets over time. The onset removal was intentionally done in a random manner, so that discovered fragments would not persist longer than a measure or two. For the decay phase of this track, the initial six minutes were time-reversed to provide the same level of randomly omitted onsets.

Since all psychoacoustic ability growth for this track is linked to the MMN response, additional measures were taken to produce the response wherever possible. If the entire sound track was played out a single speaker, the brain would begin to expect further stimuli from that location. One of the techniques utilized in the Beat Induction track was to pan the onsets between the two physical installations with Digital Performer 6 software. This dramatic shift of location will change the amplitude and latency of the sound arriving to each corresponding ear, which are two additional triggers of an MMN response (Wunderlich 1526); our installation is not limited to producing MMN based solely on the beat, but also on the volume and location of the sound source.

Finally, to keep this track firmly in the background environment and not in the forefront of thought, the original MIDI instrument set that created the stock GarageBand band was altered. Instead, a more unconventional instrument set was chosen so the beat was less easily recognized as a traditional music sample. If a listener had begun to hear the underlying hip hop styled instruments, cultural influences or emotional attachment would draw conscious attention to track and lessen the desired background nature of the stimuli.

The "Bars and Ambiance" track consists of algorithmically generated bass tones that are masked by an upper layer of ambient sound effects and traditional music snippets. The main focus of the Bars and Ambiance track is to create difference tones that lead to brain entrainment in the alpha range. The 10 Hz difference tone is created with bass frequencies in a similar fashion to traditional binaural beats, and the ambient layer helps prevent the repetitive bass tones from drawing attention to itself (perhaps in the form of annoyance).

The bass track is divided between the two physical installations; the first's subwoofer is responsible for a 40 Hz tone, while the second system outputs 50 Hz. Each installation plays its respective bass note for five seconds and is silent for one, and the two installations' are staggered so there are periods of simultaneity as well as one second sections where only one tone is heard.

Particularly during the overlapping bass sections, the two notes combine to form a difference tone of 10 Hz in the listener's perception. As mentioned previously, this frequency lies in the alpha range and leads to a brainwave entrainment response. Without two independent subwoofers, this effect would be difficult or impossible to create because summating the tones at a single subwoofer driver can be potentially damaging for the speaker and leads to a noticeable loss of quality. Furthermore, the physical separation of the two subwoofers more closely imitates the binaural experiments conducted by hearing researchers; the brain performs more processing when it is forced to synthesize the difference tone from two different ears (Pratt 41).

The ambient layer was also pieced together in GarageBand and varies between traditional music blocks, sound effects, and silence. The assemblage was randomly done, so the lengths of each section and the order between them follow no discernable pattern. Following the thematic thread of this project, these steps were taken to minimize attention devoted to the installation and allow the psychoacoustic ability growth to occur naturally in the subconscious. Furthermore, the familiarity of ambient layer (in particular, the traditional musical snippets) establishes a comfort zone in the listener; by introducing known stimuli in conjunction with the unfamiliar psychoacoustic, the listener's consciousness can remain undisturbed.

The final track, "Sweeps and Scales", was completely generated algorithmically in MATLAB (see Appendix A for full code listings for the functions utilized in this project). As with Bars and Ambiance, there is a bass layer that is entirely beneath the 120 Hz crossover of the Altec Lansing speakers used, and a treble layer to cover the remainder of the frequencies. This track is also the only one of the three to utilize all six of the available channels between the two installations. At any point, all the audible stimuli are separated from one another by 10 Hz to provide a similar brain entrainment function as in Bars and Ambiance. However, since five to six tones are playing simultaneously with these frequency separations, the perceived 10 Hz tone is more truly a missing fundamental tone than the simple difference tone of Bars and Ambiance. The background research indicates that this will induce a stronger perceived tone and should be more effective in entraining listeners' brains.

The bass layer again utilizes the independence of the dual subwoofers that is unique to our 4.2 speaker design. One installation plays a 40 Hz bass tone while the other is responsible for a 50 Hz tone with periods of overlap and periods of individuality. In contrast to Bars and Ambiance, these are not single-volume pulses, but instead surge to a peak volume and then exponentially drop back to zero; in other words, the fade-in time is much shorter than the fade-out. This creates a give-and-take effect between the installations, with neither fighting for perceptual dominance at any given time.

The treble layer is more complicated. Between the two installations, there are four discrete channels. The first channel plays an ascending and then descending A minor scale for the duration of the track (fifteen minutes). The second channel plays the same scale, but each note's frequency is increased by 10 Hz and the entire scale is delayed (with respect to the first channel) by 15ms. The third channel plays the second channel's scale, but is also higher by 10 Hz for each note and late by another 15ms. Predictably, the fourth follows the third's frequencies but is again higher by 10 Hz and delayed by 15ms. In total, this creates a 10 Hz missing fundamental frequency, and sounds like an A minor "scale" that is more dissonant at lower notes (because the 10 Hz separation is a more appreciable fraction of the note frequency) and less dissonant as it ascends. Furthermore, the offset almost creates a swing rhythm as the different channels switch frequencies at different times. The overall effect is eerie from the minor scale, especially when paired with the almost ominous bass fading. The 10 Hz missing fundamental established from the four treble channels complements and strengthens the 10 Hz difference tone between the two subwoofers, making this track particularly effective at inducing a brainwave response.

Periods of twenty-minute apparent silence were interspersed between the auditory tracks. This provides some relief from the audible stimuli, and allows the sound design to again remain in the background of the environment. Also, from a realistic standpoint, generating hours' worth of unique audible stimuli was beyond the scope of the project, and would probably have detracted from the impact of the stimuli tracks. Using the apparent silence pads the impact that the sound design has on the environment in which it is placed. The apparent silence segments are in reality one of two options: complete silence or a frequency above the audible range of human hearing. A frequency of 21 kHz was chosen because while it is inaudible to human listeners, the frequencies are still retained with traditional 44.1 kHz sampling rates. Barring the limitations of the speakers, the frequency will exist in the air and the ear regardless of whether it is perceived. While 21 kHz is not cited explicitly in research, some brain entrainment studies did demonstrated that very high frequencies can trigger beneficial reactions in the brain.

Chapter 5: Physical Construction

While the focus on this project has thus far been on the psychoacoustic research and acoustic stimuli development, the design of the physical installations is also crucial for successful delivery. From a practical point of view, the construction of two dedicated **psy**choacoustic **s**timulation **d**evices (PYSDs) serves to protect electronic components, and increase portability of the sound design. Functionally, two independent PYSDs allow convenient placement options around the environment, and our particular design features a multitude of smaller speakers to de-localize the sound source within each installation. Finally, the mere aesthetics of a well-constructed enclosure brands legitimacy in listeners' minds and enhances visual appeal. A proper sound design must not only achieve the desired audible effect, but also enhance the experience by visually complimenting the surrounding location.

To meet these requirements, the PYSDs were created based on a hollow soffit with a post extending upwards from each end. A number of angled copper pipes connect the posts in a mesh design and host an array of small speakers. The pipes also serve as convenient and discrete wire channels that route all connections back down into the soffit where the audio system is housed. Each PYSD is equipped with an Altec Lansing VS2521 28W 2.1 stereo sound system. The back face of the soffit was ported for the rear-driving subwoofer. There is also an Altec Lansing speaker mounted directly to each 4x4 post to serve as the main source of quality sounds in the installation; the smaller speakers aim to diffuse the sound rather than add to the overall volume or clarity. A mocked-up and scale design of one PYSD is shown below in Figure 18 and Figure 19.

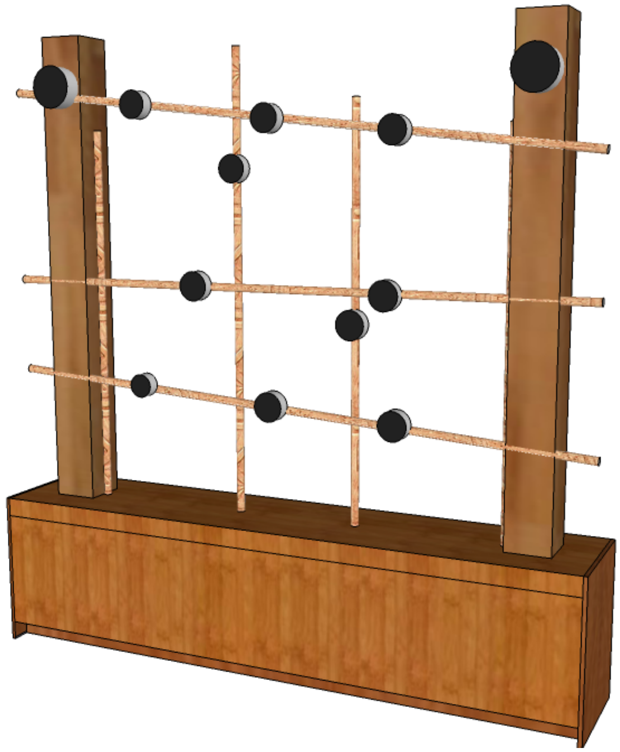

Figure 18. Front View of a PYSD

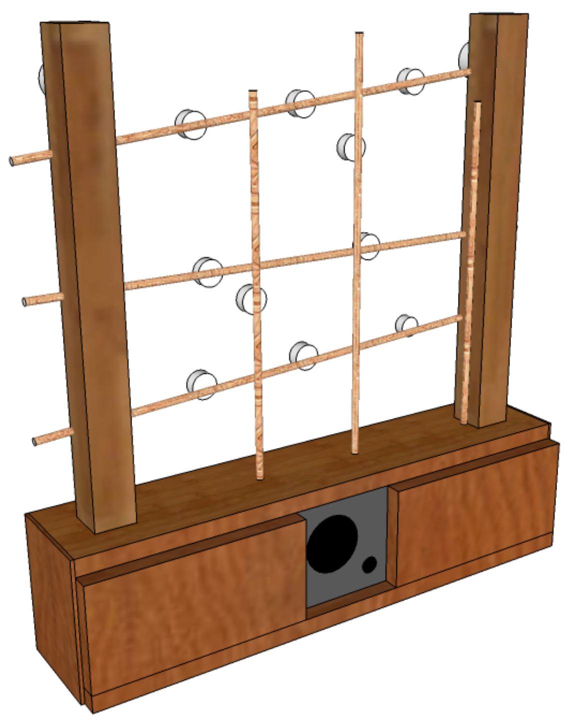

Figure 19. Rear View of a PYSD

Portability was a main concern during construction of the PYSDs so that the installations could be moved between locations with minimal effort. Each installation breaks down into three main components: the soffit, the posts, and the pipes. Wiring between components was done through 3.5mm male and female jacks for rapid connections, and to allow the Altec Lansing sound system to be easily removed and repurposed if desired. The soffit provides a secure enclosure for the sound system, the power source, and an iPod Nano to supply the acoustic stimuli. Access to these vulnerable electronic components is restricted by two hinged doors on either side of the subwoofer, and can be secured with padlocks if desired. The posts fit snugly into the soffit via padding and angle brackets, but are not permanently attached so that they can be lifted out easily. While the smaller speakers are secured to the copper pipes, the pipes themselves can be broken at a coupling at the midpoint to be pulled out of the posts during disassembly.

As far as building materials, the soffit of each PYSD was constructed of 2x12 pieces of pine with a quarter-inch wood veneer piece capping the ends. The posts are four foot sections of 4x4 pressure-treated lumber. After construction and assembly, all wood was sanded, stained, and polyurethaned to resemble finished furniture rather than a hand-built project. The copper pipes are standard half-inch plumbing conduit, and were polished with #0000 steel wool for luster. Scaled dimensional diagrams for one PYSD are shown below in Figure 20 and Figure 21.

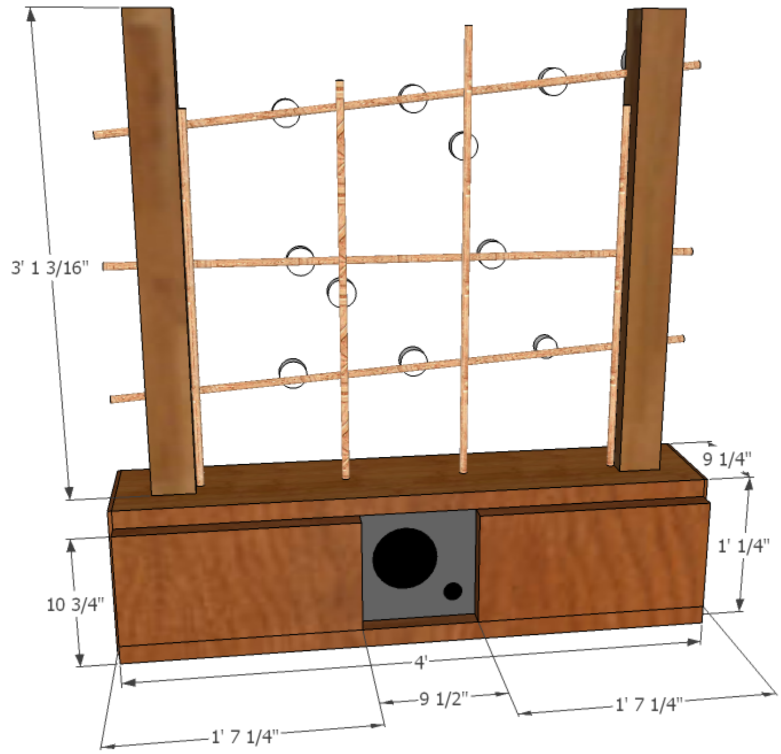

Figure 20. Dimensional Rear View of a PYSD

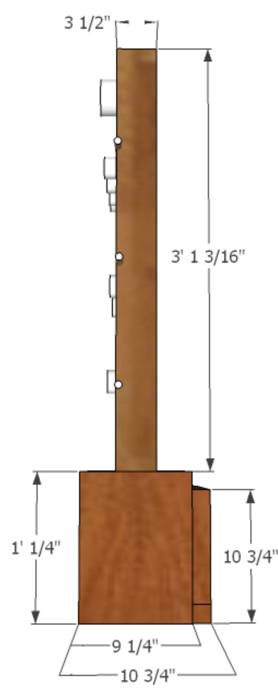

Figure 21. Dimensional Side View of a PYSD

To primarily drive the highest quality speakers, the Altec Lansing satellites were placed in series with the audio source, while the smaller copper pipe array of speakers were placed in parallel after the satellites. Considering each small speaker is 8Ω, and eight of them are wired per installation with four per channel, each parallel combination has an equivalent resistance of 2Ω. These parallel combinations were placed in series with their respective 8Ω Altec Lansing satellite, which is a negligible change in impedance from the point of view of the sound source. This results in only slightly less current to the Altec Lansing satellites, and very marginal current to each individual small speaker. An ohmmeter was used to verify the wiring configuration behaved as expected. As desired, this will disperse the sound between the two posts, while still retaining the majority of the power on the larger speakers. A visual representation of the wiring scheme for one PYSD post is shown below in Figure 22.

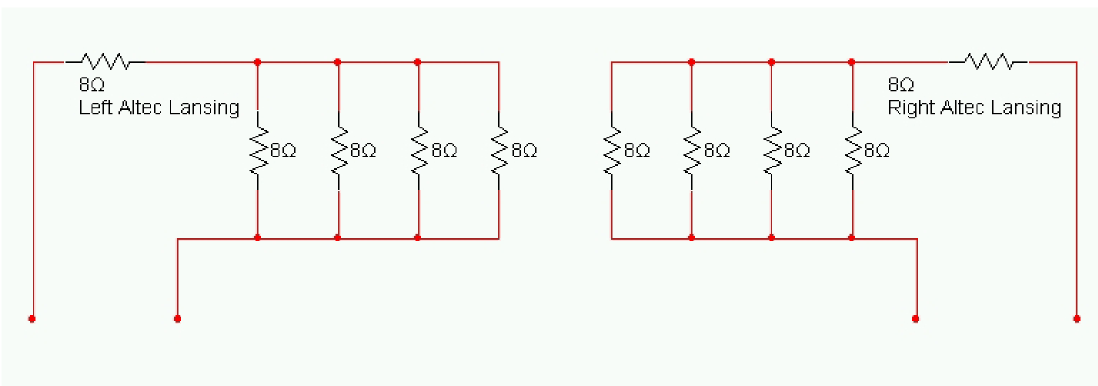

Figure 22. Wiring Diagram for a PYSD Post

Chapter 6: Discussion

Over the course of this project, two PYSDs were constructed according to design, electrically tested, and loaded with the generated acoustic stimuli. Overall, it was the opinion of the authors that the project was a success in both its physical and aural implementations. The authors initially recognized successful effects of the acoustic stimuli, and this conclusion was corroborated informally by third-party observers. Future projects could refine, research, or improve these installations; there are many opportunities for controlled analyses of the reactions and effects that the installations produce. Since our preliminary results show success, future projects could achieve similar results.

Considering that the physical installation required maximum portability, legitimacy, and compactness, the design needed special attention and foresight to avoid calamitous errors. The wire routing configuration and housing the subwoofer's fixed dimensions were the most troublesome design hurdles. Nevertheless, the final product satisfied the requirements while still appearing professional. The two physical installations are a more elegant medium to play the generated psychoacoustic stimuli samples, and are far superior to statically placing traditional speakers around a room. Our opinion is subjective, but we feel the PYSDs bring a new level of depth to stimulating human psychoacoustic ability.

Construction was conducted completely in a college apartment; unlike a guarded lab, this environment naturally has a wide variety of people trafficking in and out. For most of these people, curiosity was aimed at what was being built rather than the sounds that would eventually be played. Few had even the slightest idea of what the devices were, supporting our aim to abstract the sound design into something unfamiliar and mysterious. All agreed that the PSYDs were visually impressive, well-constructed, and would attract interest in a public environment.

Informal reactions to the acoustic sound stimuli and the sound design as a whole were an overall indication that the project was a success. The scope of this Interactive Qualifying Project never intended to include formal analysis of the effects produced by exposure to the psychoacoustic stimuli. However, our own reaction to the Beat Induction track surprised us; we found ourselves becoming frustrated over the fragmentation of the beat - whether we were consciously paying attention or not - and this feeling persisted just until the full beat became apparent. At that point, the stimulus captured our attention and became incredibly pleasant to listen to. This same effect was observed in all third-party listeners with no previous knowledge of this project; everyone began smiling or tapping their foot when the full beat became apparent, but remained unsettled up to that point. Likewise, the reverse transition is also critically noticed at the beginning of the decay region of the track.

The Sweeps and Scales track generated the most response in listeners. Although only perhaps because of the A minor scale, the track generated an extremely unsettling effect in those exposed. The overlapping frequencies create a dramatic thickness and a noticeable beating frequency in the listeners head from the missing fundamental phenomena. The low frequency sweeps are low enough that they are perceived as omnidirectional, and help delocalize the source of sounds from the installations.

Throughout the entire process, various areas of improvement were isolated but could not be addressed at this time due to time and budgetary constraints. The majority of these issues were related to the quality of the electronics; for instance, the 3.5mm jacks were inexpensive but occasionally had poor connectivity between the males and females. This wasn't surprising, but requires that each horizontal pipe of speakers must be checked by ear when the installation is turned on. The quality of the small speakers could also be improved; the frequency response is only rated for 420 Hz to 5000 Hz, and performance degrades significantly (or catastrophically) if overdriven. The most problematic hurdle with the audio system was the crossover network that was included in the Altec Lansing system. This component routes low frequencies exclusively to the subwoofer and high frequencies to the satellites and small speakers. We found that a small portion of the bass frequencies still passes to our treble network, which manifests as clipping and distortion. A superior crossover could be purchased or built had time or budget allowed; in the meantime, proper mixing alleviated the problem enough for our purposes. Finally, the 6th generation iPod Nanos that were used for audio playback did not feature an alarm clock that would allow us to synchronize the start of the stimulus playlist between the two installations.

While we were extremely satisfied with the outcome of the physical installations, the quality could have been further enhanced with more appropriate tools. Construction was limited to working with a power drill and a Sawzall saber saw. A table saw would give incredible accuracy and precision when cutting, and be much safer than the manual cut procedure used. Unfortunately, some edges are not perfectly square and the hinged doors do not make a perfect seal with the soffit body, but we feel the build quality was impressive given the available tools.

No formal experiments have been conducted using the PYSDs, but many of the applied topics of the background research could be explored further in controlled studies. One possibility would be to contain the PSYDs in an anechoic to eliminate reflections and constructive/destructive interference; this change could change listeners' reactions. Additionally, our unique design features six discrete channels in a "double 2.1" stereo configuration. Playing psychoacoustic stimuli out of such media is unexplored in the literature, so an investigation using this mode of communication would be an untapped area of research.

This project did not aim to verify the concepts outlined in earlier chapters; rather, it was a proof of concept and an artistic piece. Later projects could delve into whether the prolonged exposure to our generated stimuli leads to a quantified improvement of psychoacoustic perception, or monitor EEGs to observe the MMN response or the predicted brain entrainment at 10 Hz.

Beyond these quantifiable or measurable studies, behavioral analyses would also yield more insight into the human response to our installations and sound design. These could include a time-lapse study of people's movement patterns around - and investigation of - the PYSDs. This data could be compared against the psychoacoustic stimulus that was playing at that time to determine a relationship between the various audio tracks and interest levels. Another study could explore the visible reaction that many people have when the proverbial beat "drops," or when the rate of omitted onsets drops to zero and the overall onset frequency becomes constant. This significant event corresponds to the moment of maximum beat induction opportunity and is nearly always noticed immediately by listeners.

Chapter 7: Conclusion

The goal of this project was to design and construct both a collection of psychoacoustic auditory stimuli and two physical installations to house and complement the sound design. Research was conducted to investigate the variety of psychoacoustic phenomena that occur in the inner ear and brain, leading to our focus on difference tones, missing fundamental, beat induction, brain entrainment, and the mismatched negativity response. These effects have a likely root in the evolutionary history of humans, and studies have shown that the acuity of psychoacoustic perception can be enhanced from prolonged exposure. While this project does not attempt to quantify the growth of listeners' abilities, the acoustic stimuli are designed to stress and exercise the listener's auditory processing capabilities. Qualitative reactions to the stimuli were apparent to some degree in every listener, and quantitative analysis could be conducted by future projects or research.

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Appendix A: MATLAB Code

bars.m

```
lbase = [fadeTone(makeTone(40, 5), 0.25), zeros(1, 1*44100)];
rbase = [fadeTone(makeTone(50, 2), 0.25), zeros(1, 1*44100),
         fadeTone(makeTone(50, 3), 0.25)];
lfinal = zeros(1, 1);
rfinal = zeros(1, 1);

for i=1:150
    lfinal = [lbase, lfinal];
end
wavwrite(lfinal, 44100, 'PSD 1 Bars.wav');
clear lfinal;

for i=1:150
    rfinal = [rbase, rfinal];
end
wavwrite(rfinal, 44100, 'PSD 2 Bars.wav');
clear all;
```

scales.m

```
fade = 0.25;
r1base = [fadeTone(makeTone(220.00, 0.5), fade),
          fadeTone(makeTone(246.94, 0.5), fade),
          fadeTone(makeTone(261.63, 0.5), fade),
          fadeTone(makeTone(293.66, 0.5), fade),
          fadeTone(makeTone(329.63, 0.5), fade),
          fadeTone(makeTone(349.23, 0.5), fade),
          fadeTone(makeTone(392.00, 0.5), fade),
          fadeTone(makeTone(440.00, 0.5), fade),
          fadeTone(makeTone(392.00, 0.5), fade),
          fadeTone(makeTone(349.23, 0.5), fade),
          fadeTone(makeTone(329.63, 0.5), fade),
          fadeTone(makeTone(293.66, 0.5), fade),
          fadeTone(makeTone(261.63, 0.5), fade),
          fadeTone(makeTone(246.94, 0.5), fade)];
r2base = [fadeTone(makeTone(240.00, 0.5), fade),
          fadeTone(makeTone(266.94, 0.5), fade),
          fadeTone(makeTone(281.63, 0.5), fade),
          fadeTone(makeTone(313.66, 0.5), fade),
          fadeTone(makeTone(349.63, 0.5), fade),
          fadeTone(makeTone(369.23, 0.5), fade),
          fadeTone(makeTone(412.00, 0.5), fade),
          fadeTone(makeTone(460.00, 0.5), fade),
          fadeTone(makeTone(412.00, 0.5), fade),
          fadeTone(makeTone(369.23, 0.5), fade),
          fadeTone(makeTone(349.63, 0.5), fade),
          fadeTone(makeTone(313.66, 0.5), fade),
          fadeTone(makeTone(281.63, 0.5), fade),
```

```
          fadeTone(makeTone(266.94, 0.5), fade)];
r2base = [r2base(length(r2base)-2*3308:length(r2base)),
          r2base(1:length(r2base)-2*3308-1)];
l1base = [fadeTone(makeTone(230.00, 0.5), fade),
          fadeTone(makeTone(256.94, 0.5), fade),
          fadeTone(makeTone(271.63, 0.5), fade),
          fadeTone(makeTone(303.66, 0.5), fade),
          fadeTone(makeTone(339.63, 0.5), fade),
          fadeTone(makeTone(359.23, 0.5), fade),
          fadeTone(makeTone(402.00, 0.5), fade),
          fadeTone(makeTone(450.00, 0.5), fade),
          fadeTone(makeTone(402.00, 0.5), fade),
          fadeTone(makeTone(359.23, 0.5), fade),
          fadeTone(makeTone(339.63, 0.5), fade),
          fadeTone(makeTone(303.66, 0.5), fade),
          fadeTone(makeTone(271.63, 0.5), fade),
          fadeTone(makeTone(256.94, 0.5), fade)];
l1base = [l1base(length(l1base)-1*3308:length(l1base)),
          l1base(1:length(l1base)-1*3308-1)];
l2base = [fadeTone(makeTone(250.00, 0.5), fade),
          fadeTone(makeTone(276.94, 0.5), fade),
          fadeTone(makeTone(291.63, 0.5), fade),
          fadeTone(makeTone(323.66, 0.5), fade),
          fadeTone(makeTone(359.63, 0.5), fade),
          fadeTone(makeTone(379.23, 0.5), fade),
          fadeTone(makeTone(422.00, 0.5), fade),
          fadeTone(makeTone(470.00, 0.5), fade),
          fadeTone(makeTone(422.00, 0.5), fade),
          fadeTone(makeTone(379.23, 0.5), fade),
          fadeTone(makeTone(359.63, 0.5), fade),
          fadeTone(makeTone(323.66, 0.5), fade),
          fadeTone(makeTone(291.63, 0.5), fade),
          fadeTone(makeTone(276.94, 0.5), fade)];
l2base = [l2base(length(l2base)-3*3308:length(l2base)),
          l2base(1:length(l2base)-3*3308-1)];
r1final = zeros(1,1);
r2final = zeros(1,1);
l1final = zeros(1,1);
l2final = zeros(1,1);

for i=1:129
    l1final = [l1base, l1final];
end
wavwrite(l1final(1:44100*15*60), 44100, 'PSD 1 Scales Left.wav');
clear l1final;

for i=1:129
    l2final = [l2base, l2final];
end
wavwrite(l2final(1:44100*15*60), 44100, 'PSD 1 Scales Right.wav');
clear l2final;

for i=1:129
    r1final = [r1base, r1final];
end
wavwrite(r1final(1:44100*15*60), 44100, 'PSD 2 Scales Left.wav');
```

```
clear r1final;

for i=1:129
    r2final = [r2base, r2final];
end
wavwrite(r2final(1:44100*15*60), 44100, 'PSD 2 Scales Right.wav');
clear all;
```

sweeps.m

```
vector = linspace(0, 2, 6*44100+1);
envelope = exp(-vector);

tone1 = fadeTone(makeTone(40, 6) .* envelope .* 2, 0.35);
tone2 = fadeTone(makeTone(50, 6) .* envelope .* 2, 0.35);

lbase = [tone1(5*44100+1:6*44100),zeros(1,44100*4),tone1(1:5*44100)];
rbase = [tone2,zeros(1,44100*4-1)];
lfinal = zeros(1,1);
rfinal = zeros(1,1);

for i=1:(15*6)
    lfinal = [lbase,lfinal];
end
wavwrite(lfinal, 44100, 'PSD 1 Sweeps.wav');
clear lfinal;

for i=1:(15*6)
    rfinal = [rbase,rfinal];
end
wavwrite(rfinal, 44100, 'PSD 2 Sweeps.wav');
clear all
```

interludeSilence.m

```
wavwrite(zeros(1,20*60*44100), 44100, 'interlude.wav');
```

interludeHigh.m

```
wavwrite(makeTone(22100, 15*60), 44100, 'interlude21k.wav');
```

fadeTone.m

```
function s_tone = fadeTone(tone, fade_time)

in_start = 1;
in_stop  = floor(fade_time * 44100);
fade_in = tone(in_start : in_stop);
```

```
in_vector = linspace(-3, 3, length(fade_in));
in_env = 1 ./ (1 + exp(-in_vector));
fade_in = fade_in .* in_env;

out_start = length(tone) - floor(fade_time * 44100);
out_stop  = length(tone);
fade_out = tone(out_start : out_stop);

out_vector = linspace(-6, 6, length(fade_out));
out_env = 1 ./ (1 + exp(out_vector));
fade_out = fade_out .* out_env;

s_tone = [fade_in , tone(in_stop + 1 : out_start - 1) , fade_out];

end
```

makeTone.m

```
function tone = makeTone(frequency, duration)

t = 0 : 1/44100 : duration;
f = frequency;
tone = 0.4*sin(2*pi*f*t);

end
```