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SANTA CRUZ

IMPACT OF BINAURAL BEATS ON HEART RATE VARIABILITY

A thesis submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

COMPUTER ENGINEERING

by

Rebecca J. Rashkin

September 2018

The Thesis of Rebecca J. Rashkin is approved:

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Professor Matthew Guthaus, Chair

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Professor Luca de Alfaro

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Doctor David Munday

_____________________________
Lori Kletzer
Vice Provost and Dean of Graduate Studies
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A binaural beat is an auditory illusion that occurs when each ear is listening to a tone that is slightly different from the other ear. It is theorized that listening to binaural beats increases brain activity in the frequency range corresponding to the frequency of beats presented. Hence, individuals listen to binaural beats intending to entrain their brains to experience a specific mental state.

There has been relatively little research on how binaural beats affect heart rate variability, or the variation of time between heart beats. Heart rate variability is associated with heart health. In this thesis we present an application called SoundSlug, which generates binaural beats and records heart rate data. We conducted a study using SoundSlug where we presented 31 research participants with two binaural beat frequencies and a control condition with no binaural beats. Findings suggest that binaural beat conditions do not affect heart rate variability significantly from the condition with no beats. However, all audio conditions trended toward lower heart rate variability than the baseline silence.
To my rabbit,

Flux,

my unconditional companion.
Acknowledgments

First and foremost, I would like to acknowledge my advisor and committee chair, Professor Matthew Guthaus for his patience and guidance throughout my graduate program. His advice has helped me become a stronger academic and live my life with greater intention. I would also like to acknowledge my other reading committee members, Professor Luca de Alfaro and Doctor David Munday for their validation and suggestions which increased the quality of this thesis.

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Chapter 1

Introduction

Music can affect our emotions; an upbeat tune can lift our spirits, and a tense composition can increase stress during a difficult video game. But what are the specific aspects of music that contribute to this mood shift? And what are the physiological effects of audio on the body? We are interested in breaking down music to its rudimentary components and exploring how it affects a person’s body and mind. This chapter introduces the physiological background that motivates this work.

1.1 Binaural Beats and Brain Waves

To begin our exploration, we designed and executed a pilot study to investigate the effects of binaural beats on the heart. A binaural beat is an auditory illusion created by the brain when the ears are exposed to tones slightly out of phase from one another. The person hears a “beating” sensation with a frequency equal to the phase difference of the tones. For example, if the left ear is listening to $440\, Hz$ and the right ear $444\, Hz$, 

1
Table 1.2: Frequency ranges for brain waves during the sleep cycle are labeled as indicated in the table.

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Brain Wave</th>
<th>Sleep State</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 4 Hz</td>
<td>delta</td>
<td>deep sleep</td>
</tr>
<tr>
<td>4 Hz - 7 Hz</td>
<td>theta</td>
<td>intermediate sleep stages</td>
</tr>
<tr>
<td>8 Hz - 13 Hz</td>
<td>alpha</td>
<td>quiet wakefulness</td>
</tr>
<tr>
<td>14 Hz - 80 Hz</td>
<td>beta</td>
<td>alert wakefulness, REM sleep</td>
</tr>
</tbody>
</table>

the user would hear a beat at 4 Hz [17]. It is theorized that listening to binaural beats increases brain activity in the frequency range corresponding to the frequency of beats presented, a phenomenon called the frequency following effect [2]. Hence, individuals listen to binaural beats intending to entrain their brains to experience a specific mental state. For instance, delta waves are associated with deep sleep [9], so listening to beats less than 4 Hz is said to increase relaxation. Likewise, studies have shown that experienced meditators show an increase in theta waves during meditation [4][27], so one would listen to binaural beats in the theta range to induce a meditative state. However, as discussed in Section 2.1, the evidence for the frequency following effect is conflicting and therefore inconclusive.

Brain activity can be measured using electroencephalography (EEG), where electrodes are placed on the scalp, and the differences in electrical potentials are recorded. EEG signals are periodic and their frequency components reflect categories of brain consciousness. Frequency ranges for brain activity and their corresponding mental states as they relate to the sleep cycle are categorized as shown in Table 1.2 [9].
1.2 Baroreceptor Reflex

Studies have shown that meditation also affects heart rate variability (HRV), the variation in the time between heart beats [20][19]. Heart rate variability is strongly related to the sensitivity of the baroreceptor reflex, a component of the autonomic nervous system (ANS) [1]. The autonomic nervous system controls bodily functions that occur non-consciously such as digestion and temperature regulation. There are two components of the ANS: the sympathetic nervous system, which controls the “fight or flight” response (e.g. increased heart rate), and the parasympathetic nervous system, which is known for “rest and digest” functions (e.g. decreased heart rate). The parasympathetic nervous system contains the baroreceptor reflex (baroreflex), which facilitates automatic blood pressure regulation. Baroreceptors are nerve endings located on the interior of major arterial walls. When the sympathetic nervous system is activated, heart rate increases and blood pressure rises. The baroreceptors are stretched, which sends a signal through the nervous system to decrease the muscular force at which the heart contracts, reducing blood pressure [9].

1.3 The Heart

The heart does not beat to the rhythm of a metronome. Heart rate varies continuously due to factors including respiration, movement, and blood pressure regulation. The level of variation of heart rate indicates how effectively the circulatory system is responding to changes in the environment. The term used to describe the
duration between heart beats is called \( R-R \) or \( N-N \) interval and is illustrated in the electrocardiogram (EKG) diagram shown in Figure 1.1 [26]. An EKG graphically represents the heart’s electrical activity and is used to evaluate cardiac health. Lower levels of HRV have been associated with depression [28], mortality after heart attack [13], and coronary heart disease [5]. Relatively high levels of HRV has been associated with higher performance on cognition tests [10] and healthy longevity [31].

There are two general approaches to measuring HRV: 1) in the time domain and 2) in the frequency domain. Analyses in the time domain require straight-forward statistical calculations and determine the amount of variability. In contrast, frequency domain calculations uncover the underlying rhythms of the heart [26].

Heart rate variability measured in the time domain is based on either the time intervals in between beats or comparing the lengths of adjacent heart beat cycles [26]. Some inter-beat HRV measurements are called SDNN, SDANN, and SDNNIDX. These
measurements are influenced by short- and long-term factors. SDNN is the standard deviation of all N-N intervals, also known as cycle length variability (CLV). Another inter-beat time domain measurement is calculated by taking the standard deviation of the mean of the five-minute intervals averaged over a 24-hour period (SDANN). SDNNIDX is an intermediate measurement that takes into account short- and long-term variability by averaging standard deviation of the inter-beat intervals over each five-minute period [26].

Measurements that compare adjacent cycle lengths are impacted by only short-term factors and reflect parasympathetic activity. The percentage of adjacent cycles that are greater than 50 milliseconds is known as the pNN50. The square root of the average sum of squared differences of the time between cycles is called the r-MSSD (root mean square successive differences) [26].

Frequency domain HRV measurements reveal information about variability due to physiological oscillations with difference frequency ranges. Fourier analysis is used to decompose the heart rate signal into its frequency components. The heart rate variance (measured in ms^2) is the power in a portion of the total frequency spectrum. This spectrum can be grouped into four frequency bands: high frequency (HF), low frequency (LF), very low frequency (VLF), and ultra low frequency (ULF) [26].

HF variance has frequencies between 0.15 and 0.4Hz and is generally caused by parasympathetic activity, most specifically respiration. LF variance (frequencies between 0.04 and 0.15Hz) is strongly impacted by the baroreflex but is mediated by both the parasympathetic and sympathetic nervous systems. Both VLF (0.0033 through
0.04Hz) and ULF (1.15 \times 10^{-5} \text{ through } 0.0033Hz) bands are impacted by temperature regulation, and the baroreflex. VLF variance can be obtained by data obtained in a 15-minute interval, while a ULF measurements require an entire 24-hour reading and contains the most variance over a 24-hour period. Summing the variance in each of the four bands (HF, LF, VLF, and ULF) will produce the total power (total variance) [26].

Each frequency domain HRV calculation is strongly correlated with one or more time domain HRV measurements. HF variance with pNN50 and r-MSSD, LF and VLF with SDNNIDX, and ULF with SDNN and SDANN. For the pilot study presented in this thesis, we used SDNN.
Chapter 2

Related Work

2.1 Binaural Beats

The concept of binaural beats was first published by Gerald Oster in a 1973 volume of Scientific American. Oster studied the differences in brainwave activity when listening to monaural versus binaural beats [17]. Like binaural beats, monaural beats are auditory phenomena that occur when two slightly out of phase pitches are played together. However, with monaural beats the tones are heard simultaneously in both ears, and the beats are the result of the physical interference of the two sound waves.

Oster found that the EEG potentials evoked by binaural and monaural beats differed qualitatively and quantitatively, indicating that they are processed differently by the brain. Oster also studied the window of perception, i.e. the range of frequencies where research participants could detect the binaural beats. He found they were most easily detected around 440\(Hz\) and that the inability to detect binaural beats was
correlated with the presence of Parkinson’s disease. [17].

Several researchers have studied the frequency following effect with conflicting results. Moridis et al. observed higher power in the alpha bands of the EEG during the presentation of binaural beats in conjunction with a flashing light at the same frequency in the alpha range, $8 - 13\,Hz$ [15]. In two other studies, Puzi et al. and Kasprzak observed the frequency following effect for binaural beats in the alpha band. However, in these studies the authors did not provide an equivalent control condition for comparison [23] [12]. Lopez et al. also performed an experiment presenting binaural beats to research participants, and they measured heart rate and skin conductance in addition to EEG signals. The authors did not observe any frequency following effect in their experiment, nor did they observe any significant changes in heart rate or skin conductance during the presentation of binaural beats [14].

The experiment by Lopez et al. was one of the few studies we found that analyzed heart metrics during binaural beat exposure, and they analyzed heart rate, not heart rate variability. In another study by Casciaro et al., the authors observed increases in heart rate variability, but there was no equivalent control condition provided for comparison [2]. Also, only 10 research participants took part in this study, which is too small a sample size for conclusive results. Palaniappan et al. also studied HRV in response to binaural beats with contestable results due to their even smaller sample size of five participants [18]. There is a lack of reputable studies in the area of binaural beats, specifically in their effect on heart rate variability.
Chapter 3

Preliminary Work

3.1 Pilot Study and Prototype Testing

The main purposes for this pilot study are to: 1) investigate the impact of binaural beats on heart rate variability, and 2) test the software and hardware platform so that it may be used to study the physiological effect of other audio illusions and components of music.

3.1.1 Administration

Prior to testing, an exemption was granted from University of California, Santa Cruz’s Institutional Review Board. The study was advertised through the engineering graduate student mailing list and by word of mouth. This study was performed on 31 participants, ages ranging from 20 to 79. Participants were compensated with a candy bar after completion of the study.
<table>
<thead>
<tr>
<th>Condition</th>
<th>Left Ear Frequency</th>
<th>Right Ear Frequency</th>
<th>Binaural Beat Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>zero</td>
<td>380Hz</td>
<td>380Hz</td>
<td>0Hz</td>
</tr>
<tr>
<td>delta</td>
<td>379Hz</td>
<td>381Hz</td>
<td>2Hz</td>
</tr>
<tr>
<td>beta</td>
<td>355Hz</td>
<td>405Hz</td>
<td>50Hz</td>
</tr>
</tbody>
</table>

Table 3.1: The frequencies of the two tones for each audio condition averaged 380Hz.

3.1.2 Study Design

SoundSlug was tested by running a within-subjects pilot study with three conditions: 1) zero (control), 2) delta, and 3) beta. In all three audio conditions, the participant listened to continuous tones in each ear.

The delta and beta conditions presented binaural beats in the frequency ranges corresponding to delta and beta brain waves as listed in Table 1.2 on page 2. These binaural beat frequencies were 50Hz and 2Hz for the beta and delta conditions, respectively. The zero condition had the research participant listen to the same 380Hz tone in each ear, i.e. no binaural beat was presented. The tone frequencies for each condition are summarized in Table 3.1.

A timeline of the experiment is shown in Figure 3.1. Each condition ran for two minutes with a one-minute period of silence between conditions. We chose two minutes

Figure 3.1: The purpose of the silence between audio conditions was to allow the participant’s biometric levels to return to baseline before presentation of a new audio stimulus.
Table 3.2: We presented participants with three possible orders of audio stimulus as displayed in this table.

<table>
<thead>
<tr>
<th>Condition</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

for the audio presentation to allow enough time for the body to react to the stimulus, while keeping the overall time relatively short, given that this was a pilot study. The one-minute period of silence between audio conditions in our study replicated the design of a related experiment where the authors measured EEG signals from participants while they listened to continuous and short bursts of binaural beats[8]. However, as stated in Section 3.4.2, it might have been more effective to extend the period of time between audio stimulus conditions. R-R intervals were recorded starting two minutes before the first condition was presented and ending one minute after the finish of the last condition. As shown in Table 3.2, a $3 \times 3$ Latin square was used to counterbalance condition ordering. Each participant received a four-digit pseudorandom participant ID number, the first digit being an indicator to the program of the order of conditions.

### 3.1.3 Procedure

Participants first read and signed a consent form. Next, they were asked to fill out an online questionnaire containing the Positive and Negative Affect Schedule (PANAS) [30]. The study facilitator gave instructions on how to put on the heart rate sensor and left the room to provide privacy for the participant. After the participant was
wearing the sensor, the facilitator re-entered the room and instructed the participant
to sit in a comfortable arm chair and wear earbuds connected to a mobile phone. The
volume was adjusted to a comfortable level, and the sensor was linked to the phone
via Bluetooth. The facilitator explained in general terms what the participant should
expect to hear and instructed him or her to close their eyes and focus on their breathing.
The facilitator left the room during the audio presentation and EKG recording. Post
audio presentation, the participant was asked to fill out another online questionnaire
that contained the PANAS along with other questions. See Appendix A for the consent
form and questionnaires.

3.2 Implementation

To carry out this experiment, we designed a mobile application called Sound-
Slug that generates binaural beats and records heart rate data collected from a mobile
EKG monitor. We created a Python program to analyze the data offline after the user
study.

3.2.1 Mobile Platform

We implemented SoundSlug using a Motorola Moto E 2nd generation mobile
phone running Android version 5.0.2 and Zephyr HxM Smart mobile heart rate monitor
(HRM) using the Bluetooth 4.0 protocol, commonly known as Bluetooth Low Energy.
The phone and HRM are pictured in Figure 3.2. The HRM is a mobile EKG device
and uses the standard Bluetooth Heart Rate Service [25] specification for data transfer.
This application was developed using the native Android API version 18.

SoundSlug generates data files on a mobile device that can be imported to a laptop using Android Debug Bridge (adb) [22]. We processed the data offline using Python 2.7 on a MacBook Pro running MacOS 10.10.5. This overall process is illustrated in Figure 3.3. To generate plots, we used Matplotlib version 1.3.1 [11]. To analyze the data, we used NumPy version 1.14.0 [16] and Statsmodels version 0.8.0 [24].

Figure 3.3: After collecting data from the Android mobile device, the data must be imported to a personal computer then processed using a Python program. In future studies, we can make this process more efficient by eliminating step 2 or incorporating data processing into the mobile application.
Figure 3.4: These images display several screenshots of SoundSlug’s user interface. Instructions for putting on the sensor are shown in Sensor Setup. Sensor Connect displays the UI for connecting the sensor to the phone. In the Data Collection screen, the BEGIN STUDY button is pressed to commence heart data recording and audio presentation. The last screen notifies the participant that the data collection is complete.
3.2.2 SoundSlug Software Architecture

SoundSlug is a multithreaded application; it is comprised of a main user interface (UI) with two background processes that run on separate threads, called Intent Services in Android’s architecture. Figures 3.4 and 3.5 respectively illustrate four of the screens from the UI and the connectivity between processes. One Intent Service called WriteFile indirectly interfaces with the HRM and records heart rate data and annotations to a file on the SD card. The other Intent Service named Sound generates and plays audio.

3.2.2.1 Audio Generation

As illustrated in Figure 3.6, we used the Android SoundPool class to play tones required to produce binaural beats. The SoundPool object contains two audio streams, one for each ear. Each stream is generated using an audio file and a playback speed for pitch modulation. The sound file is a 1s 440Hz tone generated from Audacity, a free
audio editing program. The program can increase the pitch of the tone by selecting a playback speed greater than one. Similarly, to decrease the pitch, the playback speed selected would be less than one. To determine the playback speed, the program function took inputs of base frequency and frequency offset. The base frequency is the average frequency of the tones for each ear, and the offset is the difference between the two tones, i.e. the frequency of the binaural beat. The frequency for each ear is $1/2$ the offset above and below the base frequency requested. Once the appropriate frequencies are calculated, the playback speed for each stream is computed by dividing the frequency by 440. Each audiostream is looped until a function call stops the looping. The .ogg file type enables seamless looping so tones sound continuous. Audio annotations are added to the file to indicate when tones or silence begins.

3.2.2.2 Data Collection

To obtain heart rate data, we modified BluetoothLeService, an example class from the Android developer website that enables interfacing with any Bluetooth 4.0
sensor [21]. As shown in Figure 3.5, the UI thread of SoundSlug binds to WriteFile, which binds to BluetoothLeService. BluetoothLeService receives the HRM data packet and sends heart rate and R-R interval information to WriteFile, which then records these metrics to a file.

The HRM broadcasts a data packet about once every second. When the mobile device receives the data packet, SoundSlug adds a new line to the data file in the following format:

| timestamp | hh | rr | rr |

where timestamp is the timestamp in milliseconds when the phone received the data packet, hh is the average heart rate in beats per minute (BPM), and rr is the R-R interval in milliseconds. A data packet may contain one or more R-R interval measurements.

Annotations are added to the data file when audio changes. An example of an annotation is:

```
1519159009761 tones started - base freq: 379; offset: 2
```

The first number in the line is the timestamp, the base frequency is the frequency that the left ear is exposed to, and the offset is the frequency of the binaural beat. The data analysis program uses these annotations as delimiters when parsing the file.

As indicated in Figure 3.1 on page 10, heart data collection begins two minutes before the user is exposed to any audio condition. Next, the participant is exposed to two minutes of the first audio condition followed by one minute of silence. This is
Figure 3.7: The annotations are used by the data analysis program to parse the file.

repeated two more times for the other audio conditions. An abbreviated version of a
data file is shown in Figure 3.7. Note that “...” represents more lines for each condition.

3.3 Data Analysis

During the course of the experiment, we collected quantitative data in the form
of heart rate metrics and qualitative data from online questionnaires before and after
3.3.1 Quantitative Data Analysis

SoundSlug generates a data file for each participant containing average heart rate and R-R intervals sent from the heart rate monitor. These data files were analyzed using a Python program as described in the subsequent sections.

3.3.2 Top Level of Quantitative Data Analysis

Figure 3.8 illustrates the flow of the data analysis program. First, the program reads and parses the participant data files. Section 3.3.3 details how the data was read and prepared for processing. Heart rate and R-R intervals are extracted for each audio condition for each participant. All of the R-R interval data are combined into one data structure, and the SDNN is calculated for each participant, for each condition.

Next, we chose which part of the experiment to use as the baseline. For each participant, the program determined if the SDNN for conditions was less than the
baseline. We then had two categories of variables: SDNN less than baseline and SDNN greater than or equal to baseline. Based on this information, the program performs Cochran’s Q test for hypothesis testing. The null hypothesis is that conditions do not produce significantly different results from one another across participants [7]. The output from Cochran’s Q test produces a p-value that we compare to alpha to determine if the null hypothesis should be rejected.

3.3.3 Read File

Before data analysis, the program reads and parses the data file. The function `read_file` reads a single file and outputs a list of data structures that contain the R-R interval and heart rate data: `hr_list`, `rr_list`, `rr_post_silence`, `rr_pre_silence`, `all_rr`. With the exception of `all_rr`, elements in the output list are lists of dictionaries. Dictionaries are used because not all participants were exposed to the audio conditions in the same order. The use of key value pairs allows the measurements to be grouped with the appropriate condition regardless of order of presentation.

This program was designed to allow for an experiment with multiple phases where each phase could have differing lengths of time between types of audio stimulus. However, since the main objective of this pilot study was to test the hardware and software platform, we chose to implement a simple one-phase study where audio stimuli were presented between periods of silence.

Each object in the list output from `read_file` corresponds with a participant and is a list of dictionaries, with each element in the list corresponding to a phase of the
Figure 3.9: Each entry in the overall list corresponds with a participant. Only the first
4 R-R intervals are shown for each audio condition.

experiment. Because there was only one phase in this experiment, each participant data
entry has only one dictionary. Each key-value pair in the dictionary contains a key that
is equal to the condition: silence, zero, delta, or beta. The corresponding values are
a list of measurements, either R-R intervals, or heart rate values. Figure 3.9 shows an
abbreviated version of \textit{rr\_list} to illustrate the organization of the entire data structure.

### 3.3.4 Data Preprocessing

After the program reads the file, SDNN, the standard deviation of all R-R in-
tervals, is calculated for each participant for each of the four conditions and the periods
of silence between audio intervals. For ease of data processing, the data is converted
into a NumPy array with each row corresponding to a participant and each column
.corresponding to a condition. The column numbers correspond with the following con-

```python
[
  [
    {'beta': [956, 944, 944, 996, ...],
     'zero': [952, 964, 984, 984, ...],
     'silence': [836, 876, 856, 784, ...],
     'delta': [916, 876, 880, 860, ...]},
  [
    {'beta': [732, 700, 692, 732, ...],
     'zero': [788, 712, 684, 692, ...],
     'silence': [812, 856, 844, 764, ...],
     'delta': [716, 696, 712, 752, ...]},
  [
    {'beta': [748, 756, 740, 756, ...],
     'zero': [680, 688, 708, 720, ...],
     'silence': [664, 664, 672, 668, ...],
     'delta': [684, 688, 708, 704, ...]},
  [...]
]```

```
<table>
<thead>
<tr>
<th>SDNN Data</th>
<th>Binary Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>[49.52, 53.61, 48.25, 46.11]</td>
<td>[1, 1, 0]</td>
</tr>
<tr>
<td>[85.04, 66.98, 42.78, 42.91]</td>
<td>[1, 1, 1]</td>
</tr>
<tr>
<td>[37.22, 26.44, 24.74, 72.47]</td>
<td>[1, 1, 1]</td>
</tr>
<tr>
<td>[30.74, 17.86, 21.98, 23.03]</td>
<td>[1, 0, 1]</td>
</tr>
<tr>
<td>[95.31, 57.17, 32.45, 25.11]</td>
<td>[1, 1, 0]</td>
</tr>
<tr>
<td>[147.08, 123.31, 96.32, 108.47]</td>
<td>[1, 1, 1]</td>
</tr>
</tbody>
</table>

Table 3.3: The left array shows the SDNN data values for the four conditions (columns) across six participants (rows). The binary array on the right is the result of comparing the delta condition (the third column in the left array) to the other conditions.

...
3.3.5 Cochran’s Q Test

Cochran’s Q test is a non-parametric statistical test used to compare the outcome of conditions based on a categorical variable [3]. It is similar to the Chi-squared test, but different in that it tests a dichotomous variable and can be used to compare more than two conditions. The Statsmodels function *cochrans_q* uses the binary array described in Section 3.3.4 as an input and outputs a Q-statistic and p-value. The null hypothesis is that two or more conditions did not produce significantly different results. We compare the p-value to the threshold value of $\alpha$; if the p-value is less than $\alpha$ we can reject the null hypothesis.

We performed Cochran’s Q five times; in the first four tests we compared each audio condition to the other audio conditions and the initial silence. In the last test we compared each audio condition (zero, beta or delta) to the period of silence preceding it. As discussed in Section 3.4, the results of these tests suggested that there was no significant difference between HRV calculations as compared to the selected baseline condition.

3.3.6 Qualitative Data Analysis

We calculated positive and negative affect scores from the self-reported participant data before and after the EKG recording. In addition, we calculated the hedonic ratio, the ratio of scores for positive to negative affect, before and after the experiment. The differences between the hedonic ratios from before and after the experiment were compared to the differences in SDNN from the periods of silence before and after all
3.4 Results and Discussion

3.4.1 Audio Compared to Initial Silence

In this section, references to baseline refer to the SDNN measured during the initial period of silence before the first audio condition. Our hypothesis was that the binaural conditions would produce significantly different results from the control (no beat) audio condition as compared to initial baseline silence. However, our results did not confirm this hypothesis. When using Cochran’s Q test to compare the three audio conditions against the baseline, the calculated p-value was 0.779. This p-value is orders of magnitude larger than a typical $\alpha$ of 0.05 or 0.1, suggesting that the binaural conditions did not affect the HRV much differently than the control audio condition with no binaural beats.

Though the findings from this first statistical test contradicts our hypothesis, we made some interesting observations. For both the control and experimental conditions, SDNN trended towards lower than the baseline. Out of the 31 total participants in this study, the number of participants that had lower SDNN than baseline was 23 for the zero condition, 25 for the delta condition, and 24 for the beta condition. The average decrease in calculated SDNN between the audio condition and baseline was 29.2ms for no beat condition, 34.0ms for delta beat condition, and 34.1ms for beta condition. This suggests that audio has the potential to affect HRV.
3.4.2 Audio Compared to Preceding Silence

The possibility exists that exposure to audio from a previous condition could affect the results of a subsequent condition. To compensate for this possible discrepancy, in our second analysis we compared the SDNN calculated from each audio condition to the SDNN calculated during the period of silence preceding it. In this section, the baseline refers to the SDNN calculated from the R-R intervals of the silence preceding an audio condition. Cochran’s Q test yielded a p-value of 0.368, further supporting the conclusion that the audio conditions did not produce significantly different results from one another. When comparing the SDNN values directly, the number of participants with SDNN lower than baseline was 21, 15, and 19 for the zero, delta and beta conditions, respectively.

It should be noted that participants were only exposed to one minute of silence between conditions, which might not have been enough time to allow the body to return to the pre-audio state. SDNN calculations for the silence period after audio conditions trended lower than the initial period of silence. The number of participants with SDNN lower than initial silence was 23 for the silence period after the zero condition, 25 for after the delta condition, and 24 for after the beta condition. Of the participants with lower SDNN during these silent transition periods, the mean differences were 61.97 ms for after the zero condition, 58.12 ms for after the delta condition, and 61.84 ms for after the beta condition.
3.4.3 Conditions Compared to Audio Conditions

In the previous sections, we used the SDNN calculated during the initial silence as a baseline and not as a condition to compare against the other conditions. Therefore, in our final three tests we used each of the audio conditions as a baseline and compared them to the initial silence and other audio conditions.

3.4.3.1 Zero Condition as Baseline

In the first of the last set of tests we compared the initial silence condition and each of the two binaural conditions to the zero condition. Out of 31 participants, the number with a calculated SDNN greater than the zero condition baseline was 23 for silence, 19 for delta, and 16 for beta. The p-value calculated from Cochran’s Q test was 0.07. If we consider an $\alpha$ of 0.1, we can say there is a statistically significant difference between at least two of the conditions tested.

3.4.3.2 Delta Condition as Baseline

When using delta as a baseline and comparing it to silence, zero, and beta, 25, 19, and 16 participants had SDNN greater than baseline for each condition, respectively. The results of Cochran’s Q test yielded a p-value of $4.4e - 4$ which is much lower than an $\alpha$ of 0.05 or even 0.01, which means we can say there is a difference between at least two of the conditions with 99% confidence.
<table>
<thead>
<tr>
<th>Baseline</th>
<th>silence</th>
<th>zero</th>
<th>delta</th>
<th>beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-statistic</td>
<td>0.5</td>
<td>5.29</td>
<td>15.4</td>
<td>7.88</td>
</tr>
<tr>
<td>P-value</td>
<td>0.779</td>
<td>0.07</td>
<td>4.36e-4</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 3.4: The p-values when using baseline audio conditions suggest there were significant differences between conditions.

### 3.4.3.3 Beta Condition as Baseline

In the last test we used beta as the baseline and found that 24, 15, and 17 participants had an SDNN greater than baseline for silence, zero, and beta conditions, respectively. The p-value resulting from Cochran’s Q test was 0.02, once again suggesting that there is a significant difference between at least two of the conditions as compared to the baseline. The p-values and Q statistics from the tests in this section are summarized in Table 3.4.

### 3.4.4 Positive and Negative Affect Schedule

The PANAS was administered before and after the entire experiment and not after each individual audio condition. Therefore, results from this section can only be associated with the study experience as a whole, without considering any of the conditions individually. Out of 31 participants, 30 reported answers on the PANAS. The changes in positive and negative affect are summarized in Table 3.5. The majority of participants reported a decrease in positive affect. The same number of participants reported a decrease in negative affect as the total number who experienced an increase or no change in negative affect. In addition, the hedonic ratios decreased for the majority of participants.
Table 3.5: This table summarizes the the number of participants who reported changes in positive and negative affect, and the average increases and decreases in affect scores from those participants.

We were interested in the results from participants who practice meditation and yoga, because both of these practices involve bringing awareness of how external stimulus impacts a person’s internal environment. We believed that participants who train in these mindfulness exercises might be more impacted than other participants. Five participants reported some sort of regular meditation practice though the degree of practice was not clear. Two of these participants reported experience with meditation in the context of a strong yoga practice (three or more times per week). These participants had an increase in SDNN for the binaural conditions and a decrease in SDNN during the control condition as compared to the initial silence condition. The changes in SDNN were $14.71\text{ms}$ and $14.63\text{ms}$ for the delta condition, $32.3\text{ms}$ and $0.75\text{ms}$ for the beta condition and $-31.7\text{ms}$ and $-9.51\text{ms}$ for the control condition. The second of these two participants had prior knowledge of this experiment and binaural beats.

<table>
<thead>
<tr>
<th></th>
<th>number of participants</th>
<th>affect score</th>
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<td></td>
<td>increase</td>
<td>decrease</td>
<td>no change</td>
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<tr>
<td>positive affect</td>
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<td>19</td>
<td>0</td>
</tr>
<tr>
<td>negative affect</td>
<td>7</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>hedonic ratio</td>
<td>13</td>
<td>17</td>
<td>0</td>
</tr>
</tbody>
</table>

28
Chapter 4

Conclusion and Future Work

In this thesis we presented an experiment to determine the effect of binaural beats on heart rate variability (HRV), a metric associated with cardiac health and emotional well being. We designed a study that compares HRV of participants during an initial period of silence and three audio conditions: two experimental conditions and a control condition. In the experimental conditions we presented binaural beats in the ranges for delta and beta brain waves. Our initial hypothesis was that presentation of binaural beats in comparison to an equivalent control condition would have a significant effect on HRV. In contrast to this hypothesis, we observed that the binaural beat conditions did not affect HRV significantly in comparison to the control condition. We used Cochran’s Q test for statistical comparison, and calculated p-values that did not suggest rejection of the null hypothesis. However, we did observe that all audio conditions trended towards lower HRV than the initial baseline silence.

Participants reported their current emotional state before and after the ex-
periment using the Positive and Negative Affect Scale. Overall, for the majority of participants we observed a decrease in positive affect and a decrease in the ratio between positive and negative affect. The majority of participants also experienced a decrease in HRV when comparing before and after all of the audio conditions.

There are many variables that should be considered when reporting these results. It is possible that the environmental conditions of the experiment itself had a more profound effect on results than the difference in audio conditions. Some participants reported that participation in the study was "scary" given that they were to sit in a dark, unfamiliar room listening to ominous tones. In another study, we could change the environment to have a soft light in the background.

For the most part, in the periods of silence between audio conditions, HRV rarely returned to prior audio exposure levels. Another experiment could include longer periods of silence between conditions to allow heart rate to return to initial baseline conditions.

In addition, prior knowledge about the study has the potential to bias results. The consent form indicated that the study was about audio and its effect on the heart. It is possible that this information could have affected the outcomes. In another experiment, we could investigate the effect of how priming users with information about the study affects the body’s reaction to binaural beats or other audio phenomena.

It is possible binaural beats more evidently affect those who already have strong meditation experience or similar practice. The sample size of participants with meditation experience was too small to draw conclusive results from, so it might be
worth designing a new experiment that is directed at the effect of binaural beats on
experienced meditators in comparison to others who lack this experience.

There are many directions we could take for future studies using SoundSlug. In our experiment, we chose frequencies around 380\,Hz which we based off of a related study where the authors investigate the effect of continuous and short bursts of binaural beats on EEG signals [8]. It is possible that specific frequencies or combinations of frequencies affect the heart in different ways. We could redeploy this experiment using different base pitches or offsets to produce binaural beats that align with different brain waves. Many of the commercially available binaural beat audio tracks include beats that are overlaid against music or other ambient sounds. We could also investigate the physiological response differences between the beats in isolation, ambient sounds, and beats overlaid against ambient sounds.

SoundSlug could also be used to study how different audio illusions and patterns of frequencies affect HRV. Music and sound effects are carefully chosen for entertainment and interactive media, often to heighten arousal levels and increase engagement during intense scenes. This is especially evident for the genres of suspense and horror, where lower frequencies are often played before a quick increase in pitch to enhance the shock factor. Previous studies have reported that participants that listen to songs in minor modes report higher arousal than when listening to major mode music[29]. SoundSlug can be used to further explore this research space to study not only how static frequencies affect the body, but how dynamic changes in pitch, rhythm and volume affect the autonomic nervous system. Findings from these experiments could be

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considered when creating soundtracks for movies, television shows, and video games.

The software and hardware platforms were effective in data collection and analysis, though there is room for improvement in terms of efficiency and software design. In future studies, we could have data files transferred directly to the personal computer for analysis, or the data analysis could be incorporated into the mobile application directly. In addition, we could modify the audio generation portion of SoundSlug to create or playback other types of audio and give the researcher the option of changing the audio stimulus from the front end.

The results of this pilot study suggest that listening to computer-generated tones, binaural or not, negatively impacts heart rate variability. A redesign and deployment of this experiment might give more conclusive results on the effect of binaural beats on the heart. In addition, the SoundSlug software framework can potentially be reused for other research applications involving studying the effect of stimulus on heart rate variability.
Bibliography


samples/BluetoothLeGatt/src/com.example.android.bluetoothlegatt/BluetoothLeService.html.


Appendix A

Study Materials

This section includes the consent form and questionnaires administered during the pilot study.
CONSENT TO PARTICIPATE IN RESEARCH

Introduction
You are invited to take part in a research study conducted by Rebecca Rashkin overseen by Associate Professor Matthew Guthaus from the Computer Engineering Department at the University of California, Santa Cruz. Before you decide to participate in the study, read this form and ask questions about anything you do not understand.

Purpose
We are investigating the effect of audio on the body. We hope the results of this study can inform future design decisions on health related applications.

Procedure
The first part of this study is to take an online questionnaire. Next, you will be asked to wear a commercially available mobile heart rate monitor across your chest. The study facilitator will instruct you on how to put it on. You will sit in a chair and put on ear buds or headphones connected to a mobile device. Sample audio will be played so volume can be adjusted to a comfortable listening level. Afterwards, the mobile device will output a combination of silence and audio. The heart rate monitor will take measurements and send the data to the phone. Stored data will be anonymized. After the audio is presented, you will be asked to take another short online questionnaire.

Time required
Participation in this study will take approximately 45-60 minutes.

Risks and benefits
There are no anticipated risks in this study. Although there will be no direct benefit to you for taking part in this study, the results will help the researcher in designing health related applications.

Confidentiality
The information that you give in the study will be anonymous. Your name will not be collected or linked to your answers.
**Decision to quit at any time**
Your participation in this study is completely voluntary. You do not have to participate. Even if you decide at first to take part, you are free to change your mind at any time and quit the study. Whatever you decide will in no way affect your academic standing, and if you are participating as a course requirement, you will still receive credit for the study.

**Questions and contact**
If you have any questions about this research, please contact:

Rebecca Rashkin
Ph.D. Student
rrashkin@ucsc.edu

You may also contact the faculty member supervising this work:

Matthew Guthaus, Ph.D.
Associate Professor
(831) 406-1851
mrg@ucsc.edu

If you have any questions regarding your rights as a research participant, please contact:

Office of Research Compliance Administration
University of California, Santa Cruz
(831) 459-1473
orca@ucsc.edu

**Signature**
Signing this document means that you understand the information given to you in this form and that you voluntarily agree to participate in the research described above.

__________________________________________
Signature of participant             Date

__________________________________________
Printed name

**Please sign both consent forms, keeping one for yourself.**
Pre-Study Questionnaire

Thank you for participating in our study! Please fill out the following questionnaire.

* Required

1. Have you read and signed the informed consent form? *
   
   Mark only one oval.
   
   ○ Yes
   ○ No

2. What is your participant ID number? *

Demographics

3. What is your age? *

4. Gender *
   
   Mark only one oval.
   
   ○ Male
   ○ Female
   ○ Prefer not to say
   ○ Other: ____________________________

Recent Activities

Please let us know if you’ve engaged in the following activities recently.

5. Check all that apply. In the last two hours, have you: *
   
   Check all that apply.
   
   ○ ingested caffeine or other stimulant? (e.g. coffee, black or green tea, Excedrin, Adderall)
   ○ exercised for at least 45 minutes?
   ○ eaten?
   ○ taken a quiz or test?
   ○ given a presentation?
   ○ I have not engaged in the activities listed above.
Current State
Read each item and select the appropriate number to indicate to what extent you feel this way at the present moment.

6. Interested
   Mark only one oval.
   
   1 2 3 4 5
   very slightly or not at all extremely

7. Distressed
   Mark only one oval.
   
   1 2 3 4 5
   very slightly or not at all extremely

8. Excited
   Mark only one oval.
   
   1 2 3 4 5
   very slightly or not at all extremely

9. Upset
   Mark only one oval.
   
   1 2 3 4 5
   very slightly or not at all extremely

10. Strong
    Mark only one oval.
    
    1 2 3 4 5
    very slightly or not at all extremely

11. Guilty
    Mark only one oval.
    
    1 2 3 4 5
    very slightly or not at all extremely
12. **Scared**  
Mark only one oval.

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13. **Hostile**  
Mark only one oval.

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14. **Enthusiastic**  
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15. **Proud**  
Mark only one oval.

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16. **Irritable**  
Mark only one oval.

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17. **Alert**  
Mark only one oval.

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18. **Ashamed**  
*Mark only one oval.*

1 2 3 4 5

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19. **Inspired**  
*Mark only one oval.*

1 2 3 4 5

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<th>very slightly or not at all</th>
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20. **Nervous**  
*Mark only one oval.*

1 2 3 4 5

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<th>very slightly or not at all</th>
<th>extremely</th>
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21. **Determined**  
*Mark only one oval.*

1 2 3 4 5

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<th>very slightly or not at all</th>
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22. **Attentive**  
*Mark only one oval.*

1 2 3 4 5

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<tr>
<th>very slightly or not at all</th>
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23. **Jittery**  
*Mark only one oval.*

1 2 3 4 5

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<tr>
<th>very slightly or not at all</th>
<th>extremely</th>
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</table>
24. **Active**
   Mark only one oval.

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<td>very slightly or not at all</td>
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25. **Afraid**
   Mark only one oval.

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</table>

**Thank you!**

Please press the submit button below, and notify the study facilitator that you are finished with the pre-study questionnaire.
End of Study Questionnaire

Please fill out the following questionnaire.

* Required

1. What is your participant ID number? *

Current State

Read each item and select the appropriate number to indicate to what extent you feel this way at the present moment.

2. Interested
   
   Mark only one oval.
   
   1  2  3  4  5
   
   very slightly or not at all extremely

3. Distressed
   
   Mark only one oval.
   
   1  2  3  4  5
   
   very slightly or not at all extremely

4. Excited
   
   Mark only one oval.
   
   1  2  3  4  5
   
   very slightly or not at all extremely

5. Upset
   
   Mark only one oval.
   
   1  2  3  4  5
   
   very slightly or not at all extremely
6. **Strong**  
Mark only one oval.

1 2 3 4 5

very slightly or not at all extremely

7. **Guilty**  
Mark only one oval.

1 2 3 4 5

very slightly or not at all extremely

8. **Scared**  
Mark only one oval.

1 2 3 4 5

very slightly or not at all extremely

9. **Hostile**  
Mark only one oval.

1 2 3 4 5

very slightly or not at all extremely

10. **Enthusiastic**  
Mark only one oval.

1 2 3 4 5

very slightly or not at all extremely

11. **Proud**  
Mark only one oval.

1 2 3 4 5

very slightly or not at all extremely
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<tr>
<td>12. Irritable</td>
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<td>13. Alert</td>
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<td>14. Ashamed</td>
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<td>15. Inspired</td>
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<td>16. Nervous</td>
<td>Mark only one oval.</td>
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18. **Attentive**  
Mark only one oval.

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19. **Jittery**  
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21. **Afraid**  
Mark only one oval.

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22. **What do you think this study was about?**

________________________________________________________________________
________________________________________________________________________
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23. **What do you know about heart rate variability?**

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
24. What do you know about binaural beats?


25. What is your experience with meditation?


All finished!
Please press the submit button below, and notify the study facilitator that you are finished with the questionnaire.
Appendix B

Raw Data

This section includes plots of the raw R-R data recorded for all participants. The vertical lines in the plots indicate approximate times for the segments of the experiment as illustrated in Figure 3.1.