EMPATHIC EFFECTS OF AUDITORY HEARTBEATS: A NEUROPHYSIOLOGICAL INVESTIGATION

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EMPATHIC EFFECTS OF AUDITORY HEARTBEATS: A NEUROPHYSIOLOGICAL INVESTIGATION

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The two mirrors
  reflect each other.

Sōiku Shigematsu, trans.

I dedicate this thesis to my wife, Claire Riggs Miller.

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ABBREVIATIONS

AAC	Augmentative and Alternative Communication
ASD	Autism Spectrum Disorder
ANOVA	Analysis of Variance
CFA	Cardiac Field Artefact
ECG	Electrocardiogram
ECS	Emotional Contagion Scale
EDA	Electrodermal Activity
EEG	Electroencephalogram
EOG	Electrooculogram
ERP	Event-Related Potential
ERSP	Event-Related Spectral Perturbations
GLMM	Generalized Linear Mixed Model
HEP	Heartbeat-Evoked Potential
ICA	Independent Component Analysis
IRI	Interpersonal Reactivity Index
IRI	Inter-R Interval (ECG)
ITC	Inter-Trial Coherence
OR	Orienting Response
PCA	Principle Component Analysis
QRS	Prominent deflections of the ECG trace.
RMET	Reading the Mind in the Eyes Task
RV	Residual Variance
TAL	Talairach (Coordinates)
TEQ	Toronto Empathy Questionnaire
XDF	Extensible Data Format

SUMMARY

In the past century, musicians have explored various creative and aesthetic practices centered around making the sound of the body audible. An open question is whether these sounds can influence audiences' perception of the performer's emotional state or increase their sense of connection to the performer. If so, then these sounds and mapping strategies could be leveraged as an *empathic technology*—a more general class of technologies capable of modulating empathic connection between people.

The heartbeat is an easily recognizable sound with many structural similarities to the beat of music. Importantly, like musical tempo, a fast heartbeat is associated with greater affective arousal than a slow heartbeat. Recent research in music has highlighted the significance of empathy in music listening and engagement. From this research, I hypothesized that hearing the heartbeat of another person could alter listener's empathic state through its tempo.

To test this hypothesis, I designed a controlled, randomized, human-subjects experiment (N = 27) to quantify the effects of auditory heartbeat exposure on transient empathic state. The experiment paired 36 affective images of eyes with two heartbeat sounds (slow and fast) and included two reference conditions (silence & audio-only). For each trial, participants completed a task to measure the cognitive and affective components of their transient empathic state. I found significant changes in cognitive empathy and increases in affective empathy due to the auditory heartbeat, its tempo, and its congruency with the visual stimulus.

To complement these behavioral results, this experiment also analyzed effects of the exposure to auditory heartbeats on listeners' cardiac neurophysiology (i.e. ECG and EEG). The results generally showed a significant decrease in heartrate due to the auditory heartbeat, suggesting listeners became more relaxed. There were various other differences in heartrate attributable to the tempo of the heartbeat, the congruency of the audio-visual

stimulus, and self-reported affective empathy. I also found a significantly more negative heartbeat-evoked potential (HEP), which I attribute to a decrease in listener's attention to their own heart when listening empathically to the heart of another person.

Altogether, these results support the utility of the auditory heartbeat as an empathic technology. Hearing the heartbeat of another person can change affective perspective and increase affective connection. Furthermore, auditory heartbeats modulate listener's cardiac neurophysiology by slowing heartrate and decreasing cardiac cortical attention. More research is needed to fully understand these effects and their relationship to empathic state. I hypothesize that tempo forms a link between auditory heartbeat and musical beat that underlies these empathic and neurophysiological changes.

CHAPTER 1

INTRODUCTION

1.1 Music, Empathy & the Heart

Why is the heart a prominent metaphor of feeling in music? Why does the beat of music resemble the beat of the human heart? Although there are no simple answers to these complex cultural questions, this thesis posits a relationship between the heart and music that may underlie these phenomena. Namely, music and the heart are cultural loci of empathy, and tempo forms a basic link between physiology and emotion that can be felt and shared with other people.

1.1.1 Empathizing with Music

Although music is not another person, prominent theories have recognized empathic mechanisms in music listening [1, 2]. For example, music might be heard as if it were a superexpressive voice [3], and the beat, rhythms and phrasings of music might be heard as gross-motor movements and gestures [4, 5]. Beyond these structural elements, listeners can empathize directly with the performer through their expression, and with the composer through their composition [6]. Vocal music offers particularly rich ways of empathizing—lyrics can enrich music with detailed personas, narratives and social contexts [7, 8].

Empathizing with music is often embodied through corporeal imitation and synchronization [9]. For example, singing along to a favorite song (e.g. "Karaoke") requires a complex auditory-motor-affective synchronization to structural elements of the music. Cognitive and affective elements combine, increasing empathic engagement with the music [10]. Corporeal empathy is also exhibited in dance, where movement and gesture express dancer's embodiment of the music and often synchronize to the music's beat [11].

Like singing, dancing is also a complex auditory-motor activity that can lead to feeling and expressing the affect of the music [12]. Dance clubs are a clear example of music empathizing in groups. Supported by changes in neurochemistry [13], group synchronization can lead to feelings of cohesion and empathy with other dancers [14]. Other groups such as choirs, orchestras and bands are examples of groups synchronizing and empathizing through music-making [15]. And even when alone, empathetic listeners can still be “with” the music by engaging with its social content [16].

Outside of dance clubs and other overt displays of music empathizing, it is still possible to empathize without moving one’s body [17, 18]. An example of this *internal* empathizing can be found in the audiences of classical music concerts, where listeners engage with music with little observable movement. In this route, music results in physiological changes in listeners who perceive and feel the affective content of the music [19]. These internal changes can be detected using neurophysiological sensors that track changes in the autonomic nervous system and brain (e.g. [20, 21]). This thesis explores changes in the neurophysiology of the heart in particular.

1.1.2 Empathy & the Heart

In a basic sense, empathy is attention and identification with the affective, mental and physiological states of others [22, 23]. An important physiological signal of affect is the tempo of the heartbeat (i.e. the heartrate, [24]) . As part of the autonomic nervous system, changes in heartrate reflect sympathetic and parasympathetic activations, resulting in increases and decreases in heartrate respectively [25]. The heartbeat is not usually perceivable, but if hearing a heartbeat can signal different affective states in another person, it might have the same empathic effect as more common affective signals (e.g. tone of voice, facial expression [26]). Namely, hearing another person’s heartbeat might alter a listener’s perspective on what that person is feeling and result in shared feelings with that person [27].

If there are affective shifts in the listener due to the auditory heartbeat, these might be reflected in changes in their physiology. A similar phenomena is already present in music, where a complex mixture of affective non-speech auditory cues [28], can produce affective and physiological shifts listeners [19, 20, 29]. Although there are several ways of measuring changes in physiology, this thesis focuses on changes in the listener's heart in particular. This design allows the quantification of empathic effects of one heart on another heart as mediated by auditory heartbeat tempo (i.e. heartrate). In particular, empathic listening to the heartbeat of another person might arouse or relax a listener, an affective shift that would be reflected by a relatively faster or or slower heartrate [30]. If faster or slower heartrates were associated with faster or slower auditory tempos, this would provide evidence of physiological "entrainment" to tempo, a phenomenon of interest to current theories of affect induction in music listening [31].

If someone attends to the heartbeat of another person, it is possible that their subconscious attention to their own heart (i.e. "interoception") is subsequently reduced [32, 33]. Although this reduction in internal cardiac attention cannot be measured directly, it might still be measured indirectly through the brain [34]. A new brain-imaging technique called the "Heartbeat-Evoked Potential" reflects subconscious processing of the heart [35]. Prior research has shown that it becomes more negative when attention is directed away from the heart or towards the affective state of others [36, 37, 38].

1.2 Thesis Overview

1.2.1 Background

I begin this thesis by framing auditory heartbeat sharing in light of the convergence of three core application areas (Chp. 2):

1. Heartrate Sharing (Sec. 2.1)
2. Biomusic (Sec. 2.2)
3. Music Interventions for Autism (Sec. 2.3)

Section 2.1 reviews research on the social and emotional effects of sharing heartrate information in everyday contexts. Researchers have explored visual and non-visual modes of conveying this information and have demonstrated effects on receivers' cognitive and affective empathy towards others (e.g. [39, 40]). Section 2.2 grounds research on auditory physiological signal sharing in the aesthetic roots of *Biomusic*, a 20th century performance practice wherein music is generated from signals of the nervous system [41, 42]. New technologies have made these performer-audience interactions more accessible [43], and recent work has begun to examine the effects of biomusic as an intervention for alternative and augmented communication (AAC) [44, 45]. Given the responsiveness of people with autism spectrum disorder to the emotional content of music (e.g. [46, 47]), the acoustic rhythmic pattern of auditory heartbeats might assist this population in understanding the affective state of others (Sec. 2.3).

My work also has important links in empathic listening to music and tempo in particular. Chapter 3 describes various intersections in empathy, neurophysiology and music research that support my work:

1. Empathy & Measurement (Sec. 3.1)
2. Empathy in Music (Sec. 3.2)
3. Mechanisms for Empathy in Musical Emotions (Sec. 3.3)
4. Effects of Tempo & Empathy on Physiology (Sec. 3.4)

Empathy is a fundamental human capacity that has begun to be studied using psychological and neurophysiological frameworks (Sec. 3.1). Especially important to this work are the questions and methods relating to the measurement and triggering of changes in empathic state (Sec. 3.1.2). In light of this work, the auditory heartbeat of another person can be considered as an *exteroceptive* signal (Sec. 3.1.4) that might affect *interoceptive* processing (Sec. 3.1.3) as measured by the Heartbeat-Evoked Potential (HEP, Sec. 3.1.6).

Empathy in music is tied up with theories of music's ability to activate social cognition and produce pro-social effects (Sec. 3.2). Group "musicking" is associated with group cohesion, cooperation and coordination (Sec. 3.2.1). There are neuro-chemical changes that occur while engaging with music that foster social interactions [13], and it has been shown that participation in musical groups increases empathy [48]. Empathy is also active in the experience of music listening. It has been shown that empathic dispositions and traits are predictive of music preferences (e.g. [49], Sec. 3.2.2), and various theories (including Embodied Music Cognition [9], Sec. 3.2.3) suggest that music can be listened to socially, as if it were a body, person or group of people (e.g. [1, 6], Sec. 3.2.4).

Contemporary research into emotions in music listening (Sec. 3.3) distinguish between recognized and felt emotions, which are in many ways similar to the cognitive and affective components of empathic state (e.g. [50], Sec. 3.3.1). In Section 3.3.2, I argue that there are two mechanisms for music emotion induction that are relevant to the study of the empathic effects of auditory heartbeats: Emotion Contagion (Sec. 3.3.3) , and Rhythmic Entrainment (Sec. 3.3.4). Both predict similar results on the physiology of the listener, namely autonomic physiological entrainment of the listeners' heartrate to the tempo of the auditory heartbeat. Music also has the ability to alter the perception, memory and emotion of visual scenes (Sec. 3.3.5), which I use in the experiment through an audio-visual condition associating auditory heartbeats with the eyes of other people.

By focusing on the auditory heartbeat, my study investigates the effects of empathy and tempo in particular (Sec. 3.4). Tempo is a fundamental structural element in music, vital to rhythm, expectancy and temporal form [51]. Importantly for our study, it is also a strong acoustic cue of arousal in music [3, 28, 52]. Certain theories of music stipulate that the affective association of fast heartbeats to high arousal was likely learned through exposure to the mother's heartbeat in utero (e.g. [53]) and continues to develop through exposure to music after birth (Sec. 3.4.1). Several studies have shown that music, and tempo in particular can modulate arousal in listeners, particularly through the heartrate (Secs. 3.4.2

& 3.4.3). By contrasting effects of slow and fast auditory heartbeats, my study explores whether heartbeat tempo produces "physiological entrainment" in listeners in an empathic listening context (Sec. 3.4.4).

1.2.2 Research Summary

In Chapter 4, I raise several questions for the field of auditory heartbeat sharing. In general, I was curious if hearing the auditory heartbeat of another person would change listeners' empathic connection to them. I hypothesized that the auditory heartbeat would be an empathetically active signal, altering listener's perspective on what the imagined person was feeling (i.e. cognitive empathy), and increasing their ability to "feel what the other was feeling" (i.e. affective empathy). I hypothesized that these changes would be accompanied by changes in listener's neurophysiology, particularly by changing their heartrate and making the heartbeat-evoked potential more negative. To test these hypotheses, I made a multimodal behavioral and neurophysiological experiment (Chp. 5) that paired auditory heartbeats with images of eyes, and asked participants what the virtual person was feeling. To register their empathic response, I recorded two behavioral measures for each trial, as well as their electrocardiogram (ECG) and electroencephalogram (EEG).

My data largely confirmed the hypotheses. Chapter 6 showed that listener's empathic state was affected due to the presence of the heartbeat and its tempo. Listener's perception of the virtual person's affect changed (cognitive empathy), and they reported higher levels of co-feeling (affective empathy). Chapter 7 showed that there were changes in listener heartrate associated with hearing the auditory heartbeat. In general, listeners' heartrates decreased due to the auditory heartbeat, but within auditory heartbeat conditions, higher levels of empathy were associated with relatively higher heartrates. Chapter 8 showed differences in the heartbeat evoked potential between visual and audio-visual conditions. A dipole that resolved to the anterior prefrontal cortex was more negative, consistent with other findings showing that higher empathy was associated with decreased internal attention to their own heartrate (interoception). These individual results are connected and discussed in the broader research context in Chapter 9, and Chapter 10 concludes the document with a summary of core contributions, broader impact, intellectual merit and suggestions for future work.

CHAPTER 2

CONVERGING APPLICATIONS

2.1 Heartrate Sharing Applications

2.1.1 Physiological Signal Sharing

Technologies for sharing affect form an important part of the contemporary technological landscape [54]. The increasingly nuanced reactions, gifs, and emojis available in social media, and the prevalence of video calling speak to a desire and utility for diverse forms of affective connection to others [55]. Although common modes of affective communication involve facial expressions, gestures, speech and language, an alternative source of information is available in physiological signals. Sharing these signals with others has been termed physiological social signal sharing [56].

Relevant to this work, an important trend in physiological signal sharing has involved the heartrate signal [57, 58, 59, 60, 61, 62, 63]. A recent mainstream example is the Apple Watch, which shares a wearers heartrate through a heartbeat animation synchronized to their heartrate (See Fig. 2.1).[1] Other physiological signals such as skin conductance [45, 64, 65], breath [66, 67] and EEG [68] have also been explored individually and in combination (e.g. EDA, ECG, EEG [69]). Throughout these studies, the ability of the physiological signal to alter perception of the other is established, sometimes within the context or goal of empathy-building [65, 70]. To limit the scope of this literature review, I focused on works that have researched the effects of heartrate sharing in particular.

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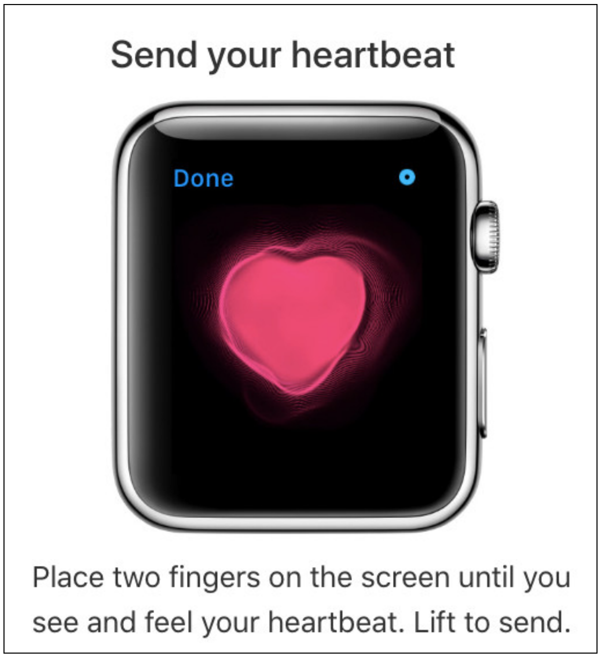
[1] [Available Online:] https://support.apple.com/en-us/HT204833, Date Accessed: September 20, 2019.


Send your heartbeat

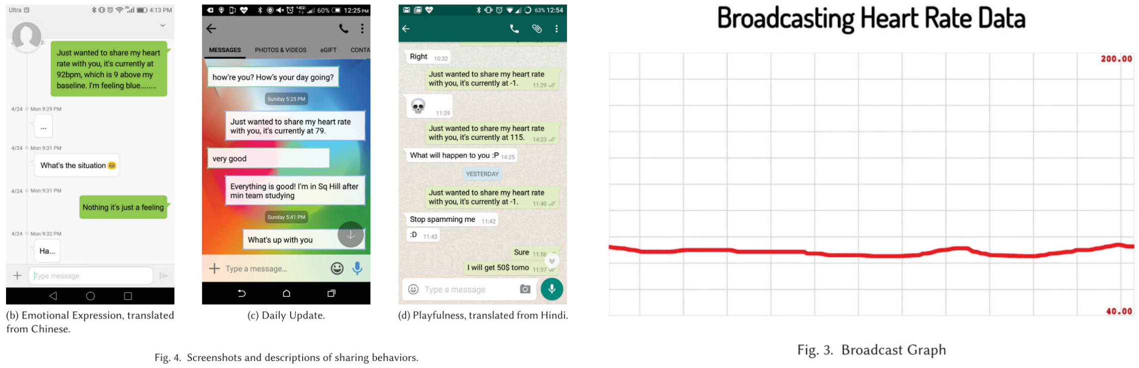
Place two fingers on the screen until you see and feel your heartbeat. Lift to send.

Figure 2.1: Heartrate sharing has appeared in mainstream technologies. The Digital Touch app on the Apple Watch enables heartrate sharing through a synchronized animation of a beating heart.

2.1.2 Visual & Textual Heartrate Sharing

Recent works have studied the effects of heartrate sharing in text messaging applications [61, 62, 70, 63]. For example, [62] developed an Android application connected to a wearable heartrate monitor. The application allowed heartrate sharing through either a preformatted text-message describing the wearer's heartrate, or in a live-streamed broadcast mode (See Fig. 2.2). The application allowed them to apply the Experience Sampling Method to understanding the use and consequences of heartrate sharing in a group of 13 participants. They found their participants used the cues for psychological and emotional communication, and that the effects of sharing included meaning-making, concern and opened communication. Adding to this finding, Hassib et. al [61] found that heartrate sharing in text messaging could support empathy, especially between already intimate people.

Although previous work had shown that heartrate sharing increased intimacy [58, 71, 39], Merrill and Cheshire [60] hypothesized that there would be different effects based



Just wanted to share my heart rate with you, it's currently at 92bpm, which is 9 above my baseline. I'm feeling blue........

4/24 Mon 9:29 PM

...

4/24 Mon 9:31 PM

What's the situation 😁

4/24 Mon 9:31 PM

Nothing it's just a feeling

4/24 Mon 9:32 PM

Ha...

(b) Emotional Expression, translated from Chinese.

how're you? How's your day going?

Sunday 5:25 PM

Just wanted to share my heart rate with you, it's currently at 79.

very good

Everything is good! I'm in Sq Hill after min team studying

Sunday 5:41 PM

What's up with you

(c) Daily Update.

Right 10:32

Just wanted to share my heart rate with you, it's currently at -1. 11:29

💀 11:29

Just wanted to share my heart rate with you, it's currently at 115. 14:23

What will happen to you :P 14:25

YESTERDAY

Just wanted to share my heart rate with you, it's currently at -1. 11:40

Stop spamming me 11:42

:D 11:43

Sure 11:56

I will get 50$ tomo 11:57

(d) Playfulness, translated from Hindi.

Fig. 4. Screenshots and descriptions of sharing behaviors.

Fig. 3. Broadcast Graph

(a) Sharing heartrates in text messages

(b) Broadcasting a realtime heartrate graph

Figure 2.2: Two examples of visually-mediated heartrate sharing explored in [62].

upon context and heartbeat tempos. They created vignettes involving a fictional acquaintance with whom they are about to see a movie (non-adversarial) or resolve a legal dispute (adversarial). In both cases, the person sends a text message saying they are running late, and the smartphone informs the participant that they have either a normal or elevated heartrate. They found important effects of heartrate upon perceived emotion and trust, but a diversity of associated meanings associated with the two contexts. This result emphasizes the complexity of meanings that may arise in the context of real-world heartrate sharing.

2.1.3 Laboratory Studies of Non-Visual Heartrate Sharing

One of the first to explore the effects of heartrate sharing was Werner et. al [58], who represented heartrate through synchronized vibrotactile feedback. They prototyped a set of two rings that could measure the wearer's heartrate and subsequently vibrate their partner's ring at the same rate. In a qualitative study involving 28 people, they reported that participants generally enjoyed the feeling of the heartbeat, especially due to its connection to their partner. However, the device also raised issues relating to trust and privacy and not all users were comfortable sharing their heartrate at any moment. This novel system was the first to explore the prospect of continuous realtime heartrate sharing and to demonstrate that the sharing of the heartrate was associated with intimacy.

Recent research has also studied the effects of auditory heartbeats in particular [71, 39, 72]. One of the key insights provided in his work is that heartbeats (and other physiological signals) are key indicators of affect, that could be leveraged to increase social connectedness, especially intimacy. For example, Janssen et. al [71] used virtual reality and behavioral measures to quantify the effects of auditory heartbeat sharing in a realtime face-to-face context. They found that the effect of hearing someone's heartbeat (versus silence) had similar effects on of self-reported ratings of intimacy as seeing someone's eyes and being in close proximity to them. In a subsequent experiment, they explored the effects of *meaning* by either telling participant that the heartbeat was an artificial sound they downloaded from the internet, or the heartbeat of a confederate in the room. In the latter case, participants kept a further distance from the confederate. The researchers attributed this to compensating for the increased intimacy provided by the heartbeat.

Effects of Acoustic Parameters

Janssen [72] extended this work through laboratory studies of the effects of different sound parameters of heartbeats on emotional intensity. He studied the effects of hearing ten heartbeat tempos, nine levels of heartrate variability, combinations of heartbeat tempo and heartrate variability, and the effects of heartrate on angry versus neutral emotional expressions. The results showed that heartbeat tempo was the biggest driver of emotional intensity. These results could be attributed to a fight or flight response, wherein heartbeat tempo is an indicator of sympathetic nervous system activation due to a perceived threat. This study did not distinguish between recognized and felt emotions. It is possible that the participants had a sympathetic response to the faster heartbeats, which would also create an increase in ratings of "emotional intensity."

My study had many similarities to these studies. However, I combined two auditory heartbeat tempos with 36 different facial affects. I also quantified the user's cognitive and affective state due to different multimodal combinations and analyzed listener's physiological response to the stimulus.

2.1.4 Towards Empathic Technologies

Slovák et. al [39] provided the first study to explore the effect of heartbeat sharing over long periods of times and outside of laboratory conditions. They gave five couples pairs of heartrate sensors that could wirelessly connect to laptops running feedback software that could take the form of visualizations and/or sonifications. The couples used the system over the course of two weeks, journaling their experiences along the way and reporting back for a formal interview after the two weeks had concluded. The researchers focused on the interpretation of the heartbeat signal and found two fundamental dimensions:

1. Heartrate as information
2. Heartrate as connection

Heartrate as information meant that the heartrate was able to convey information to the receiver about the other's affective state. In heartrate as connection, the presence of the heartrate was to generate increased feelings of connection with the other. Together, these results increased the understanding of the intimacy effects of heartrate sharing, specifically separating its components along cognitive and affective dimensions. These two dimensions were vital to my study. However, I cast them in the more general psychological form of cognitive and affective empathy and quantified their changes across many trials and audio-visual conditions.

Previous research has shown that heartrate sharing can modulate feelings of intimacy and connectedness, and these had been related to the heartrate as a source of affective information [39, 71] However, none of these works explored the effects of heartrate sharing in a way that specifically leveraged contemporary scientific understandings or methodologies related to the measurement of empathy.

To that end, Janssen developed the concept of *empathic technologies* [40]. Empathic technologies mediate human-human interactions to assist or augment human's natural empathic abilities. The field would leverage insights and methods from Affective Computing [73] and Social Signal Processing [74] but would focus on human-human social interaction as opposed to human-machine. By focusing on empathy, they were also able to organize the field around core concepts in psychology and neuroscience [75]. This prior work proposed a typology of applications and evaluation strategies for empathic technologies that involved three components:

- Cognitive empathy
- Emotional convergence
- Empathic responding

Cognitive empathy involves the recognition of mental and emotional states such as Theory of Mind [76]. Emotional convergence is related to affective empathy, especially those relating to mimicry, synchronization and contagion. Finally, empathic responding relates to the desire to alleviate distress (e.g. sympathy).

In light of this theoretical work, this thesis presents a study that quantifies the effects of heartrate sharing along two axes: cognitive empathy and emotional convergence (i.e. affective empathy). It is the first of its kind to utilize a controlled study on multimodal (i.e. visual and auditory) perception involving 36 different facial expressions and four auditory basic conditions (i.e. silence, audio-only, AV-fast, AV-slow). This allowed quantification of listening effects that sampled a broader set of emotions than could occur in face-to-face heartrate sharing. Furthermore, by utilizing physiological recording, I searched for physiological differences associated with different listening conditions and empathic states.

2.2 Biomusic: Physiology Driven Music

Many of the mediated forms of heartrate sharing that have been researched have used visual modes such as text messaging [61, 62], visualizations [63, 39, 77] or realtime graphs [59, 62]. Although these works have contributed to understanding the social effects of heartbeat sharing, relatively few of them actually used heartbeat sounds [71, 72] or rhythmic vibrations [57, 58]. These visualizations of heartrate are in contrast to common sensory experiences of the heartrate as rhythmic vibrations (i.e. tactile or auditory). The relative lack of using sound for representation of heartbeats is an oddity but may reflect broader cultural trends surrounding the roles and functions of seeing and listening [78, 79]. By contrast to these previous works, this research contributes to understandings of the effects of auditory heartbeats. It also distinguishes itself by leveraging prior scientific and aesthetic work in music, and the effects of empathy and tempo in music listening in particular.

2.2.1 Musical History

An important area of prior work on auditory physiological signal sharing is in the history of biosignals in musical and artistic expression [41, 42]. Many musical instruments have been made that are controlled by body signals, and a subset of these tap directly into signals from the autonomic nervous system (e.g. heartrate). These signals are created without conscious control or effort and reflect the performer's internal physiological state.

The use of bio-sensing for musical applications began in the 1960s when a group of prominent composers and musicians began incorporating them into musical performances [41]. Composers including Alvin Lucier, David Rosenbloom, Richard Teitelbaum and Pierre Henry were among the first to explore the aesthetic possibilities of the medium [42]. Two early works that used ECG were Teitelbaum's *Spacecraft* (1967), which used EEG and ECG to control musical and synthesis parameters of a Moog synthesizer. Rosenboom's *Ecology of the Skin* (1970) used the EEG and ECG of performers and audience members in a live performance. In the late 1980s, Knapp and Lusted [80] developed the *BioMuse* system, which introduced the concept of biosignal *control*, which was most readily demonstrable using EMG sensors. The developers commissioned Atau Tanaka to write and perform a piece. The piece, *Kagami*, premiered at Stanford University in 1989.

2.2.2 Contemporary Instruments

Since these early performances, the increased availability and accessibility of microprocessors, physiological sensors and computer-music software has resulted in many more biomusic systems [43]. Biosensing now forms an important part of the contemporary landscape of digital musical instruments and new interfaces for musical expression [81]. In the context of this work, instrument designers, composers and performers utilize many signals (often in parallel) such as the electrooculogram (EOC), skin temperatures, electromyography (EMG), galvanic skin response (GSR), electrocardiograms (ECG) and electroencephalographs EEG [82, 80, 83], even piezoelectric sensors [84].

In a slightly different but related approach, physiological data is first analyzed to recognize the emotions of a performer, and then transformed into music. So called affective music generation systems [85] or sonifications of emotion [86] use this higher-level "emotion-data" in lieu of a direct mapping of lower-level physiological signals. The resulting music may then use acoustic cues established from research on emotion in music to help the sound evoke the desired emotion in the listener. Emotion or mood can also be used as an input to a music recommendation system [87] resulting in playlists or selections of music pieces that evoke or convey a particular emotion.

Collectively, these works bear much creativity and innovation, but few have scientifically examined the effects of biomusic on listeners. This prospect is difficult as such creative and aesthetic systems are not usually designed with scientific inquiry in mind. To this end, I introduce a controlled experimental protocol that associates an auditory stimulus with a virtual person, and tests for empathic and physiological effects in listeners.

2.2.3 Biomusic Interventions

When used in a musical performance, biomusic results in "sharing" the physiological information of a performer with an entire audience. However, this sharing can also occur in more intimate settings such as with a loved one or therapist. In these settings, accurate and fast communication is a key objective, and the underlying goal is often empathetic—understanding or connecting with a person better through a realtime stream of their physiological signals.

To this end, Tennant et. al [88] proposed two mechanisms whereby biomusic can have an empathetic effect. The first was by facilitating psychophysiological entrainment. The second was by providing additional information to help mental (cognitive) state attribution. These are two functions that I hoped to address in this study, namely through the modulation of affective and cognitive empathic state. While noting that people subconsciously entrain to visual cues such as rocking, tapping, speaking and posturing, he also notes how these factors have positive effects on affiliation, empathy, cooperation and altruism. Furthermore, that skin conductance, heartrate, EEG and breathing become synchronized during interpersonal processes. Because these physiological signals are not readily perceptible, it is not possible to research a causal role in their empathic or physiological entrainment without technological mediation. The authors also suggest that there will be a limitation due to the difficulties of interpreting sounds associated physiological sensing such as skin-conductance and EEG. By focusing on the sound of the heartbeat, I avoided this problem.

Blain-Moraes et. al [44] described a musical interface for communicating biosignals from people with Profound Multiple Disabilities (PMD). Their interface mapped signals from the autonomic nervous system, namely electrodermal activity, skin temperature, blood volume pulse (BVP) and respiration. These signals were then used to control pitch height, key, tempo and phrasing in a continuous musical sequence. In an interview-oriented study involving three people with PMD and ten caregivers, the caregivers reported that the music created feelings of connectedness, co-presence and reciprocity.

In another study, Cheung et. al [45] formally evaluated a biomusic system that was designed to assist in the recognition of anxiety in children. The interface mapped electrodermal activity to melodic pitch, skin temperature to musical key, heartrate to drum beat and respiration to a “wooshing” sound. With less than 10 minutes of training, a group of 16 adult participants were able to differentiate anxious versus relaxed states with a classification accuracy of $80.8 \pm 2.3\%$ and recognize anxious states within 12.1 ± 0.7 seconds. Of the various physiological signals that were mapped into music, participants reported that the pitch (i.e. electrodermal activity) was the most useful in determining anxiety state.

Unlike these biomusic systems, the intervention I explore makes use of one physiological signal (i.e. heartrate) and one simple musical feature (i.e. tempo). As such, it is much simpler in design. However, if empathic state can be modified using just this signal and acoustic cue, it would speak to the power of the heart and tempo as loci for empathic connection. The simplicity of this strategy might also be advantageous in contexts when a more minimal musical texture is preferable, or when clarity and objectivity are prized over musical nuance.

Biomusic for Individuals

Other biomusic systems have been designed for individual use. For example, Edilgiriyeva et. al [89] described a system that composed music whose tempo was synchronized to the heartrate of the listener. Other systems have composed music whose phrases synchronize with the respiration phases of the listener [90, 91]. Generally, biomusic systems for individuals have been designed to modulate the physiology of the user. Driving the physiology of the listener to an energized or calm state can be done by choosing entire musical pieces to match the desired mood [87].

2.2.4 Ongoing Work at the Brain Music Lab

There is an ongoing research program in the cognitive, affective and neurophysiological effects led by Grace Leslie at the Brain Music Lab and Georgia Tech Center for Music Technology. This research explores a spectrum of approaches and goals for generating sound and music from physiological signals. Part of this work has developed through an expressive artistic practice incorporating sonified physiological signals (e.g. EEG, ECG and breathing) in music performance [92, 93, 94]. In a more functional route, biomusic interventions have been designed with the goal of physiological entrainment [95], which might be applied to creating more relaxed physiological states [91]. An important part of this work has also explored applications of neurophysiological signal sharing in social contexts [96, 97].

To this research program, this thesis contributes knowledge on how biomusic can produce socio-affective and cognitive changes in listeners (i.e. empathy). The neurophysiological component might contribute to our fundamental understanding of how biomusic affects listeners, which could be applied to future interventions for health and well-being.

2.2.5 Sonification of Biosignals & Affect

In general, biomusic instruments are designed with music in mind, and usually take greater artistic liberties in pursuit of their desired aesthetic. By contrast, auditory heartbeats are a more simple and direct sound, lacking rich musical structures or complex acoustic cues. As such, there are many similarities of my work to the research and design of sonification systems, which take an objective and systematic approach to the perceptualization of physiological signals [98, 99].

In general, the goal of sonification systems are to aid listeners in the interpretation or identification of information represented in an acoustic signal [99]. The stethoscope is an example of a very early technology that helped doctors listen to the body [78]. As digital technologies have developed, new ways of using the sonic information in the stethoscope have arisen [100]. As in the history of biomusic, all manner of physiological signals have been sonified, including the electrocardiogram [101, 102, 103]. However, the diagnostic character of these sonification systems leverage objective and expert listening schemes ("sonic skills" [104]) utilized by doctors, scientists and engineers [105].

One of the ways that sonification can be used is as a social medium [106], enabling one person to hear information about another. For example, footsteps are auditory signals that can cue a listener as to who someone is, where they are, what they are doing, and even that person's affective state [107, 108]. Although a sonification would take an objective approach to conveying the information, strategies from music can be used to facilitate affective communication [109, 110].

Social and cultural information and mapping strategies have recently become an important trend in the field [106, 111]. The current research contributes to this work by studying the auditory factors that influence empathic state. The heartbeat is an important cultural locus of feeling [112], and for the purposes of clear and direct communication of the virtual person's heartrate, I manipulated its tempo. Tempo is an emotionally salient musical cue [28]), and I expected that the addition of this auditory information would affect listener's perspective on what that person was experiencing, and increase affective connection to the virtual person. I further expected that the tempo of the heartbeat will act in a similar way as to musical emotion—i.e. modulating the listener's arousal.

2.3 Autism & Music

If hearing auditory heartbeats can modify empathic state, they might be applied as an *empathic technology*—a more general class of technologies capable of modulating empathic connection between people. One population that might be able to benefit from this application are people living with Autism Spectrum Disorder (ASD).

People with ASD experience difficulties in processing social information. They may have difficulties predicting other's thoughts, emotions and actions; making judgements and decisions based social information and interpreting affective cues [113]. For example, people with ASD have a reduced ability to make use of facial expressions, tone of voice, or gestures to infer another person's mental state [114, 46]. One manifestation of the disorder is an impaired Theory of Mind [115], which can manifest in reduced empathy in ASD [116].

In spite of these issues, people with ASD are notably unaffected in their musical processing abilities, and may even have strong preferences in music [46]. People with ASD are about 10 times as likely as the typical population to have savant abilities [114]. Multiple studies have found that emotional reactions of people with ASD to music are unaffected and no different than people without the disorder [117, 47].

In a prominent example, Allen et. al [118] compared physiological and verbal responses to emotional music in a group of autistic adults and found similar physiological reactions, but differences in verbalization. These results suggest that music provides cognitive and affective cues that people with autism can understand [113]. These selective deficits are important for theories of the evolutionary and biological significance of music [119, 120] and contradict arguments that people with ASD are insensitive to the emotional aspects of music [121].

2.3.1 Music Interventions

Given these results, researchers have proposed that music could be used as an effective intervention for ASD. For example, Allen and Heaton [122] proposed that the preservation of affective responses to music could be used to repair the link between autonomic and cognitive components of emotion and could be a "powerful tool" for the clinical treatment of Alexithymia. In their proposed intervention, music induces affective responses, which are associatively matched with verbal labels and later transferred to other domains.

Music has already been used as an intervention for ASD in music therapy. Therapists have successfully used music to promote interpersonal communication and relationship-building skills in children and adolescents with ASD [123], and techniques that use active, improvisational methods seem to be particularly effective. Simpson and Keen [124] reviewed the application of music as an intervention for children with autism and found that composed songs and improvisational music therapy were the predominant music techniques used.

In a different route, adding emotional music to matched visual stimuli has been shown to improve emotional attribution and recognition in people with ASD, even to the level of matched controls [117, 47, 113]. Bhatara et. al [113] compared the ability of autistic adolescents with matched controls on their ability to describe a social scene in a visual-only or an audio-visual (music) condition. Although the two groups performed differently in the visual-only condition, when the music was added, the two groups performed equivalently. Similar results were shown by Heaton et. al [117, 47], but with affective labels. Children with ASD were unimpaired in their ability to recognize happiness and sadness when paired with music in major and minor modes [117]. Similar results were found for other emotions including fear, anger, tenderness, triumph, and contemplation [47].

2.3.2 Application of the Current Work

My work shows that hearing the auditory heartbeat of another person can change the listener's affective perspective and increase their affective empathy. Because the musical abilities of people with ASD remain intact, similar empathic effects might extend to autistic populations because of the structural and affective similarities of the auditory heartbeat to the beat of music. In essence, people with ASD might be able to associate the tempo of the heartbeat with the arousal of the other person and use it to understand and connect to what that person is experiencing.

Auditory heartbeats might also be incorporated into existing applications of music therapy for people with ASD, with some key advantages. One of the key advantages of auditory heartbeats and bio-music more generally is that music can be generated automatically.

This means that people who use it do not need prior musical training, or need to give any attention to the act of making music. This quality might make auditory heartbeat sharing available to a broader set of therapists and therapy contexts. Further, auditory heartbeats can be shared in realtime. This means they can be used as an ancillary communication channel to existing visual and vocal cues.

In principle, auditory heartbeats could be applied to communicating arousal for any data-driven context. For example, an artificial intelligence system could estimate the arousal of a social scene based upon a realtime video feed, and auditory heartbeats could communicate the arousal to a user. Further, because there is little acoustic frequency overlap between auditory heartbeats (which are low in frequency) and speech (which is higher in frequency), the sound design might also complement speech without masking [125]. Compared to the relatively rich and complex textures of music, a simple tactus (i.e. tempo) might also require fewer attentional resources, allowing a user to process the auditory-affective content more efficiently.

CHAPTER 3

RESEARCH IN EMPATHY, MUSIC & NEUROPHYSIOLOGY

3.1 Empathy & Measurement

3.1.1 History & Themes

Empathy is a fundamental human capacity involving the ability to understand and feel what another person is feeling or experiencing [22]. In its most basic form it is an affective response to the directly perceived, imagined or inferred feeling state of another being [23]. Although coming into the English language from German only within the past 100 years (i.e. *Einfühlung* [126]), related notions of sympathy and emotional contagion extend to the very beginnings of Western philosophical thought [127]. Since the 1960s it has developed into an established discipline [128], with important contributions to socio-affective psychology and neuroscience [75].

Defining Empathy has been challenging, and to date there is no universally accepted definition. In their 2014 review of the concept Cuff et. al [27] identified 43 contemporary definitions and 8 major themes in the field. Broadly, the eight themes refer to i) the cognitive (recognition) and affective (feeling) components of the empathic response, ii) whether the response of the perceiver is congruent or incongruent to the observed affect, iii) whether the empathic response is exclusive to people, or if it can extend to other more abstract stimuli, iv) whether the empathic response requires a distinction between the self and the other, or if it involves some sort of self-other merging, v) whether it involves a long-term dispositional trait or is a short-term situational state, vi) whether it includes behavioral outcomes (e.g. helping), vii) whether it is automatic or controlled and viii) whether empathy can be distinguished from other psychological processes.

For the purposes of this research, my use of the term fits most closely with the definition of Empathy from the *Oxford Dictionary of Psychology* [129], which states that “[Empathy is] the capacity to understand and enter into another person’s feelings and emotions or to experience something from the other person’s point of view.”

My research also hits on several of the major themes of Empathy identified by Cuff [27]. For example, each trial includes measures cognitive and affective components of empathic state (i), and particularly whether the perceiver’s affect was congruent or incongruent with the observed affect (ii). By studying empathic effects of an an auditory heartbeat, my research also addresses the question of whether empathy extends to abstract stimuli (iii). Finally, my research addresses the relationship of short-term empathic states to long-term empathic dispositions (v) by utilizing questionnaires of empathic traits and associating them with participants’ responses to individual trials.

3.1.2 Measurement of Empathy

The scientific study of empathy requires a clear definition of empathy, and specific methods with which to study it [130]. Among the most prominent are the Interpersonal Reactivity Index [131], the Empathy Quotient [132], The Questionnaire of Cognitive and Affective Empathy [133], and the Reading the Mind in the Eyes Test [134] but there are many more. The diversity of measurement scales is rooted in many of the major trends in the field that were introduced in Section 3.1.1 including measuring different components of empathy (e.g. cognitive and affective), and accounting for congruent and incongruent reactions. These scales measure empathy as a long-term dispositional trait.

By contrast, there are significantly fewer established methods for measuring empathic state, a short-term reaction based in situational and contextual factors. One of the prominent ways of inducing an empathic state was through the perception of another’s pain or distress [135], and it is relatively common to utilize visual stimuli such as photographs or film depicting different scenes and contexts [136, 137].

My study also utilizes images of other people but modifies them by adding the sound of the observed person's heartbeat. Other instruments for measuring empathic state utilize contextual cues and scenes [136, 137], but I focused just on the facial expression in order for the participant to clearly associate the sound with a person. The Reading the Mind in the Eyes Task (RMET, [134]) is a well-established and highly used instrument that focuses on expressions of affect apparent in close-up photographs of eyes. The instrument has been useful in the diagnosis of autism and alexithymia and is thought to tap the emotional components of theory of mind in particular [138]. By pairing eyes with different auditory conditions, I determined the empathic effects of the auditory stimulus.

3.1.3 Interoception & Affect

One of the prominent theories of Empathy states that empathy is created when an observer creates a similar representation of the subject in their own body [139, 140]. Such a theory extends emotional contagion and motor mimicry to deeper physiological levels. Supporting this view, research suggests that people who are more aware of their own visceral states (interoception), are also better able to empathize with the feelings of others [140, 36].

Although the heart is often viewed as the locus for emotion from a cultural perspective, research has shown a physiological basis to that notion [112]. Schandry [141] showed that persons who were adept at feeling their own heartbeat in their body without taking their pulse also scored higher in ratings of momentary affect. The study introduced a method for testing the extent to which a person was good at perceiving their own physiological state, a perception that has been called "interoception". Subsequent analyses have demonstrated that this ability correlates with empathy [142, 143, 144, 139]. For example, Ernst et. al [145] showed that a period of focused interoceptive awareness prior to an empathy task could enhance brain-areas associated with empathy and interoception, linking these two concepts.

Although the ability to accurately perceive one's own physiological state has been shown to correlate with empathy and affect (See Sec. 3.1.3), this research differentiates itself by attributing an auditory heartbeat stimulus to another person. I hypothesized that this “exteroception” of another will have an effect on the perceiver’s empathy along both cognitive and affective dimensions. Furthermore, I predicted that hearing the heartbeat of another person will impact physiology of the observer, which may be due to the interaction of the exteroceptive and interoceptive signals.

3.1.4 Exteroception & Music

One of the questions that underlie research on empathy is the question of self-other distinction and merging [27]. Empathy seems to require both that the observer understand the emotion that another is displaying, but also to have the distinction necessary to recognize that this person is distinct. Some have argued that interoception, or the perception of one’s own physiology, is a mechanism that facilitates self-other distinction [146].

In focusing this research on the heartbeat of another person, I explored the effects of empathy as related to so-called “exteroception” [147]. Unlike interoception, which is associated with perceiving one’s internal heartbeat [148], exteroception is associated with hearing another person’s heartbeat. Due to the loudness of the auditory stimulus, exteroception is arguably more perceptually salient than the interoceptive signal, and the exteroceptive signal might alter the afferent interoceptive signal.

Furthermore, as a physiological marker of another’s affective state, the heartbeat has many structural similarities to the tactus in music [149], which have demonstrated effects on the heart of listeners (See Sec. 3.4.2). If a similar physiological effect is found here as in music, a similar psychological and physiological listening may be active in music as in my participant’s empathic listening.

3.1.5 Neuroscience of Empathy

Many of the networks underlying empathy and visceral perception are located deep in the cortex and not accessible directly using EEG [150]. For that reason, much of the neuroscientific investigations of Empathy have utilized fMRI [23, 151]. By combining fMRI with methods for triggering changes in empathic state, a host of areas have been determined to be involved in the empathetic response. These include the medial prefrontal cortex, the anterior cingulate cortex, the ventral striatum, amygdala, the precuneus, temporal parietal junction [75, 23]. These results delineate the places in the brain responsible for self and other processing and affective responses in various contexts.

Neurophysiological measurements such as EEG, EMG, ECG and GSR are also very important for the field due to their temporal resolution and measurement of the autonomic nervous system [152]. For example, one prominent EEG study of empathy was able to show that the brain-responses associated with sharing the experience of another person (affective empathy) came before those associated with mentalizing (cognitive empathy) [153]. Using EMG, researchers have shown that seeing the face of someone in pain can cause a similar facial expression in the empathic observer (emotional contagion; [154, 150]).

My study uses ECG and EEG and is therefore well positioned to investigate the temporal dynamics of the empathic response, and in terms of its effects on the autonomic nervous system. In particular, I utilized the heartrate of the observer as a means of answering a question related to emotion contagion, which is usually understood as an automatic "mirroring" of an observed affect (e.g. facial expression, posture, gesture, tone of voice) in the perceiver [155]. The heartbeat of another person is usually not observable, but if it were made observable through amplification, it might create a similar mirroring effect in the listener. I tested this hypothesis by measuring the heartrate of the listener during slow and fast auditory heartbeat presentations. If the heartrate is faster during the fast auditory heartbeat presentation and slower during the slow auditory heartbeat presentation, it would support the evidence of physiological mirroring during empathy.

3.1.6 Heartbeat-Evoked Potential

Recently an ERP has been discovered that is related to interoceptive processing, cardiac function and empathy [156, 35]. The so-called "Heartbeat-Evoked potential" is calculated by aligning epochs in a continuous EEG signal to the R-peaks in the participant's ECG waveform and removing the cardiac artifact [157]. It was first reported as a correlate for interoceptive ability [158]. People with greater interoceptive awareness had a larger positive HEP amplitude between 200-400ms over fronto-central electrodes than people with lower interoceptive abilities.

Particularly relevant for this study is the fact that empathy and perception of affective scenes modulate the HEP [36, 157, 37, 38]. In the first study to apply the HEP to emotion perception, Fukushima et. al [36] found a more negative HEP amplitude around 250ms over frontal electrodes when participants made affective judgements of faces versus a non-affective control task. Couto et. al [37] and Kim et. al [38] found similar results by contrasting positive and negative visual stimuli with neutral stimuli. Others have demonstrated that the HEP is sensitive to the predictability of affective exteroceptive stimuli [159, 33], indicating a top-down regulation of the affective response.

If the auditory heartbeat changes the heartrate of the listener, it indicates that the exteroceptive affective signal (i.e. the auditory heartbeat) has impacted the listener's physiology. Accordingly, I expected that if the listener's physiology was impacted, there would be associated changes in the HEP, which tracks the interoceptive processing. I expected that listening to another's heartbeat would affect the HEP of listeners. However, because this experiment has not been done before, I could not predict if the change will be more positive or more negative. If the change was more positive, it would indicate that the interoceptive ability had decreased due to the processing of the exteroceptive heartbeat. Alternatively, if the change is more negative, it would indicate that affective processing had increased the HEP, which has been associated with affective perception. Due to the top-down altering by expectation [159, 33], I further predicted that there will be effects of fatigue — that differences in the HEP due to the experimental conditions will decrease with repetition.

3.2 Empathy & Music

3.2.1 Music's Social Effects

Researchers interested in the biological foundations of musicality have theorized that music is evolutionarily adaptive through its social effects [160, 119]. Group "musicking" [161] can increase arousal and synchronize the moods of individuals in a group. This affective synchronization has the effect of increasing social affiliation, group cohesion, and teamwork, which presumably contributed to the survival of our ancestors. In a global context, it also has a role in cultural understanding [162] and peacebuilding [163].

These theories of the socially adaptive functions of music is supported through research on the neurochemistry of music [13]. For example, music has been shown to decrease levels of testosterone in males and increase levels of testosterone in females [164]. Testosterone is a hormone that is associated with aggression, sexuality and dominant behaviors and it's regulation through music would be advantageous for group cohesion. Music has also been shown to decrease cortisol in group singing [165], and this decrease seems to depend upon a social context [166]. Music and singing both increase oxytocin [167, 168], which has important roles in social bonding, mother-infant interactions and sexual reproduction. Listening to music also activates the endogenous opioid system (EOS), which further contributes to social bonding, perhaps through "self-other" merging [169].

By contrast to these studies, my experiment on the effects of an exteroceptive signal (music) on empathy does not make use of synchronization or musical group interaction. The rhythmic stimulus is attributed to another person, but that person is not actively moving their body to make the sound, and the listener is not moving synchronizing their movement to that person's heartbeat. Therefore, if my participants report an increase in empathy towards another person, it will be attributable to the listening alone. Furthermore, if the hypothesis that music synchronizes mood across individuals is correct, I predicted that hearing an arousing (fast tempo) or calming (slow tempo) heartbeat will synchronize the physiology of the listener.

Although my study does not track the hormone levels of listeners in response to my auditory stimulus, I did track the physiological state via the heartrate. Because music has been shown to decrease cortisol levels and increase oxytocin, I furthermore predicted that the effect of audio would be to decrease the heartrate of listeners relative to controls.

3.2.2 Empathic Traits in Music Preferences

Recent research has demonstrated the importance of empathy in music listening. One branch of research has explored whether different empathic abilities or traits could account for differences in musical preference [170]. For example, researchers have explored whether the cognitive styles of empathizing or systematizing manifested in differences in musical preferences [171, 172]. They found that people who were "empathizing" type were more likely to prefer music with low arousal, negative valence and emotional depth, while systematizing types preferred music with high arousal, positive valence and complexity. The work of Eerola et. al [49] further linked empathy to music preference for low arousal, negative valence and emotional depth. They found that people with high trait empathy and emotional contagion were more likely to enjoy listening to unfamiliar sad music.

These results predict differences in listening responses (preferences) to empathetic traits. Similarly, in my experiment, I expected that there would be differences in listening that were due to differences in empathic traits. This would create differences in self-reported responses and the resulting physiology. To test this, I distributed standard instruments for measuring empathy (see Sec. 3.1.2) and looked for correlations between the responses of listeners and their empathic traits.

3.2.3 Embodied Music Cognition & Empathy

Embodied Cognition situates the visceral and sensorimotor systems as fundamental components of consciousness and cognition [173]. This is a radically different perspective compared to traditional understandings of the body and mind as separate things (e.g. Cartesian Dualism [174]).

Understanding music in this light, Embodied Music Cognition has offered a radically different approach to music cognition that prioritizes the relationship of music to the body [9]. In this theory, the motor actions of the performer and the motor associations of the listener are tightly coupled through the act of listening [175]. Evidence for this phenomenon come from behavioral [176] and neurophysiological studies [177], which demonstrate changes in perception and neural representations of rhythms following movement.

Embodied music cognition has important implications for theories of empathy in music listening. If an engaged listener of music is making representations of the body of the performer in their own body, this provides a route for empathic connection. Namely, through embodied music cognition, the listener forms a representation of the mental or affective state of the performer and creates a similar representation in themselves.

In his book on embodied music cognition [9], Marc Leman considers empathy as part of the overall topic of imitation and corporeal effects. In his theory, although music is not a real person, the acoustic cues of music become “moving sonic forms” that are associated with actions in the listener and ascribed intentionally. Listening to music in this way is a social activity, which lends itself to empathic connection with the mental and affective states of the virtual persona represented by the music. One of the consequences of this theory is that different degrees of empathy with music will be measurable by different levels of motor and emotional engagement in the listener. Highlighting the relevance of this type of listening to music more broadly, Leman states “Embodied attuning and empathy with music are likely to open up new directions in the new field of social music cognition.”

In the present study, I provided listeners with a rhythmic auditory stimulus that represents the internal affective state of another person. Much of the work in embodied music cognition to date has focused on the effects of "motor" and "action" patterns, which are tied to the externalizations of music such as gesture [178]. By contrast, my "internal" sounds offer a means to test whether empathy with music extends to representations of internal body states as well. If my study shows that listening to these signals increase empathy and change listeners' physiology, it is evidence that embodied music cognition can extend to representations of internal physiological state.

3.2.4 Empathizing with Music

Although music itself is not a person, there are still a variety of ways that a listener could form an empathic connection with what they are hearing. For example, they could empathize with the composer through the attributing affective states to the structural cues written into the music, or with the performer through the expression and interpretation of their performance [6, 1]. Some people have argued that the listener could form an empathic connection to a "virtual persona" represented by the music itself [179, 180]. In such a theory, the structural cues of the music represent the speed, trajectory, and smoothness/jerkiness of human movement and gestures [4] forming a Shared Affective Motion Experience through the Mirror Neuron System [5, 181]. Music can also take on a narrative structure, which enables a listener to empathize with the experiences of that person [182].

For example, [6] theorized that emotion may be induced through the identification and sympathy with the expressive intentions of performers and composers. These expressive intentions are multimodal, stemming from their facial expressions, gestures, the structural cues of the music and performer's expressive interpretation. They also proposed that low-level contagion responses are possible through the rhythm, specifically through a motor synchronization.

Empathy may be key to a variety of common experiences in music: the concept of "expression" for example is related to empathy. According to Levinson [180], "expression is essentially a matter of something outward giving evidence of something inward ... the manifesting or externalizing of mind or psychology." Although music is not a literal person, it can nevertheless be imbued with cues that bring to mind another person [183]. When we hear "expression" in music we are hearing the expression of something, usually a mental, psychological or affective state.

In my work, the "music" is an exteroceptive physiological signal represented by an auditory heartbeat. This signal is paired with eyes expressing different affective states. I asked listeners to listen to the auditory stimulus as if it were the heartbeat of that person and use the sound to determine that imagined person's affective state. To my knowledge, no music study to date had performed a controlled listening study that asks listeners to hear a rhythmic auditory stimulus as if it were the internal physiological state (i.e. heartrate) of another person. If the listening experience generates a greater degree of empathy with that imagined person, a similar type of listening could be at work in engaged music listening.

3.3 Mechanisms for Empathy in Musical Emotions

3.3.1 Music Emotion & Structure

Emotion is a topic that is involved in almost every part of music including composition, performance, education, listening, therapy and research [184]. A large body of research has demonstrated that listeners are able to recognize and feel emotions in music, but questions remain as to what these emotions are [185], how recognized ("perceived") emotions become felt ("induced"/"produced") emotions [6], and especially what about music structure and listening triggers them [186].

One way to discuss emotions in music are to focus on the structural variables that coincide with perceived and felt emotions. To this end, research has shown that music is full of acoustic and structural cues that are associated with different emotions including dynamics, phrasing, melodic contour, timing, modality and tempo [28]. Among the most consistent and cross-cultural are the affective associations of tempo. The tactus or "beat" is one of the most fundamental parts of music and its tempo serves as the basic components of musical time [51]. To this end, fast tempos are associated with high arousal, energy and activity while low tempos are associated with low arousal, energy and activity.

3.3.2 Relevance of Musical Emotion to Empathy

The experience of musical emotion is not as simple as a one-to-one emotion mapping. There are a range of psychological mechanisms that can be at play when music induces an emotion in a listener [186]. To date, one of the prominent theories (ICINAS-BRECVEMAC) suggests there are nine routes to an induced emotion in music listening [2]. These include brainstem reflex, rhythmic entrainment, evaluative conditioning, contagion, visual imagery, episodic memory, musical expectancy, aesthetic judgement, and cognitive goal appraisal.

In this work, I was interested in the ways that a simple rhythmic auditory stimulus might produce changes in cognitive and affective empathy in listeners. My theory is that the psychological and physiological mechanisms behind felt and recognized emotions in music will apply to an auditory heartbeat and create changes in the cognitive and affective empathy of listeners. Of the emotion induction mechanisms in music, emotional contagion and rhythmic entrainment are the most likely. I discuss these in more detail in Sections 3.3.3 and 3.3.4.

3.3.3 Emotional Contagion & Empathy

Emotional contagion is defined as “the tendency to automatically mimic and synchronize facial expressions, vocalizations, postures, and movements with those of another person and, consequently, to converge emotionally” [155]. Particularly important for my work, Emotional Contagion has been associated with emotional or affective empathy [154, 187, 188] and is characterized by a reduced discrimination of the self and other [75]. In this psychological mechanism, the automatic mimicking of the observed affective cues in another person activates a similar affective representation in the body of the observer. This shared affective representation then gives the observer a greater perspective on the mental and affective state of another person, which increases empathy.

Emotion Contagion is an established mechanism for emotion induction in music, defined as the process “whereby an emotion is induced in a listener because the listener perceives a certain emotional expression in the music and “mimics” this expression internally” [186]. Researchers have already noted its relation to empathy [6, 189]. Although music is not a real person, musical expression often uses structural and acoustic cues that are shared with the affective qualities voice [3] and movement [4]. Hearing these qualities in music may activate a similar affective representation in the listener, causing the listener to “catch” the emotion present in the music, even enacting mental representations in their bodies [19].

The mechanism of emotional contagion has special implications for music. For example, Juslin et. al [190] performed an experience sampling study to better understand musical emotions in everyday life. When participants were asked what caused the emotion they experienced in the music, 32% of self-reported responses were *Emotional Contagion*. In a web-based experiment of over 3,164 listeners, Egermann & McAdams [50] found that self-reported empathy and emotional contagion linked recognized and felt emotions in music listening.

My experiment explores the effects of emotional contagion through the presence of slow and fast auditory heartbeats. By asking listeners to determine what the person might be experiencing based upon their heartbeat speed, I involved listeners in an empathetic listening task. I predicted that if emotional contagion was active in empathetic listening, then slow or fast auditory heartbeats would be associated with relatively faster or slower heartbeats in the listener.

3.3.4 Rhythmic Entrainment & Empathy

Rhythmic entrainment is a phenomenon wherein the beat of the music induces an emotion through temporal synchronization or entrainment of the listener. Motor and group synchronization (e.g. tapping to the beat, dancing) are the most visually apparent manifestations of rhythmic entrainment [191] and have important implications for group cohesion and affiliation (see Sec. 3.2.1). However, entrainment can also be perceived without motor entrainment, and appear in the adaptation of the autonomic nervous system towards the musical tempo [31].

In the only experimental study of its kind Labbé and Grandjean [192] explored feelings of entrainment using a 12-item entrainment questionnaire. A factorial analysis revealed an underlying 2-dimensional space that they labelled as “Motor Entrainment” and “Visceral Entrainment.” While motor entrainment was defined as the tendency to move to the beat of the music, visceral entrainment reflected listener’s feelings of bodily entrainment. The feelings of bodily entrainment might account for empathy that is not tied into the beat of the music.

Perhaps the best formulation of rhythmic entrainment as an emotion induction paradigm comes from Trost, Labbé and Grandjean [31]. Following up on their 2014 work showing different types of feelings of rhythmic entrainment [192], their work proposes four entrainment levels: Perceptual, Autonomic Physiological, Motor and Social. Autonomic Physiological encompasses the adaptation of the listener’s physiological arousal state to the arousal state represented by the musical tempo. In the absence of gross-motor movement, they argue that this type of process might stem from empathizing with the performer of the music.

It is understood that these autonomic oscillations will not be exactly the same as those of the external rhythm [31] but will instead adapt towards the target. Furthermore, that this entrainment will take longer due to constraints of the cardiovascular system. Autonomic physiological entrainment shares much in common with my hypothesis for emotional contagion (see Sec. 3.3.3). If either are involved, there will be ”mirroring” between the affective cues of the heartbeat (i.e. its tempo) and the listener’s physiology. Given the theory of autonomic physiological entrainment, I predicted a lag in the physiological change due to the constraints in the physiological system, and a shift towards the heartbeat tempo rather than exact entrainment or synchronization.

3.3.5 Multimodal Interactions

Until the 20th century, the production of musical sound was linked to a human motor action [9]. As such, in the presence of music, listeners could leverage multimodal cues for empathizing with the emotion expressed in a musical piece. Researchers have demonstrated the importance of multimodal cues in music perception [193]. Visual cues help to identify the expression of the performer in a musical piece [180], while music can alter the perception, memory and emotion of scenes and characters in film and video games [194, 195, 196, 197].

Empathy has also been implicated in the ability to use these cues to accurately identify expressive intention. In a study on the audio and visual cues of expressive performance, Wollner [17] found that observers with higher affective and overall empathy were more accurate in their identification of the expressive intentions of musicians in a quartet. These were attributed to the perception of bodily motion in particular. Prominent theories of empathy in visual art also suggest corporeal identification with the subject results in embodied reactions in the viewer [198].

In order to have a complete picture of the influence of auditory heartbeats on empathy, my study uses three modalities: visual-only, audio-only and audio-visual. Based upon the findings in music, I expected that audio will change the perception of the visuals. I also predicted that the influence of the audio will be to increase the self-reported empathy relative to the visuals alone.

3.4 Effects of Tempo & Empathy on Physiology

3.4.1 Prenatal Auditory Conditioning

The entrainment of the autonomic physiological system to a rhythmic auditory stimulus may have developed from associative experiences of the fetus in utero. The auditory system of the fetus develops in the first few months of gestation and is has matured by 24 weeks [199]. After this, the fetus can listen and learn from acoustic patterns in intrauterine sounds, which can be measured in post-natal behavior [200]. Many of the most common sounds are rhythmic and come from the mother. These include her heartbeat, breath, footsteps and voice. When patterns in these sounds co-occur with stress hormones such as cortisol, the fetus learns to associate these acoustic patterns with different affective states through classical conditioning [53].

There are many structural similarities between music and sounds in the prenatal auditory environment [201], but one of the acoustic patterns most readily associated with musical affect is tempo [28]. From very early in development a fetus may learn to associate fast gait, fast heartbeat, fast breath, fast speech with cortisol and activation of the sympathetic nervous system. Alternatively, slow heartbeat, slow breath, slow speech, slow walking would be associated with calm, parasympathetic activation. In my experiment, I explored this physiological reactivity in listeners in an empathic listening context. In particular, I hypothesized that hearing fast auditory heartbeats in another person will trigger a faster heartrate in listeners than slow heartbeats. If this occurred, it might be attributable to a bio-acoustic mirroring or contagion response, which may contribute to empathy in a similar way as other automatic contagion responses.

3.4.2 Effects of Music on Physiology

Whatever the mechanism for induction of musical emotions, there are clear relationships that have developed to the physiological reaction of the listener [19, 29, 20]. In fact, most models of musical emotion include the activity of the ANS as a core factor in the evoked emotional response [202]. Furthermore, the physiological effects of music are significantly diminished without listener's attention and engagement [203].

An old debate in music has been whether the emotions in music are true emotions (the emotivist position) or merely perceived (cognitivist position). Lyndqvist et. al [19] tested this hypothesis by measuring the emotional responsiveness of listeners physiology, facial muscles and self-report while listening to happy or sad music. All three matched the emotion expressed in the music, supporting the argument that emotions felt by listeners during music listening are real emotions.

Many studies have explored the effects of music on the heart in particular [204, 205, 206, 207]. In his 2015 review [30], Koelsch notes that music-induced emotions are associated with brain-structures known to modulate heart activity such as the hypothalamus, amygdala, insular cortex and orbitofrontal cortex [208]. He reports that exciting music is associated with higher heartrate than tranquilizing music, pleasant music is associated with higher heartrate than unpleasant music, and that HR tends to increase with music relative to silence.

Particularly relevant for this study is the fact that isochronous tones have comparable effects on the ANS as music in spite of very different pleasantness ratings [202]. This effect was demonstrated by directly comparing isochronous tones to music of the same tempo. In both cases, heartrate increased relative to silence, and the effects were indistinguishable between the two conditions. This indicates that the tactus is a primary driver of ANS activity that can produce significant changes even in the absence of other musical features.

3.4.3 Effects of Tempo on Physiology

Of the many structural features in music that might lead to a physiological response, researchers have found that tempo is a major determinant [209, 20]. Generally, emotional arousal is associated with activation of the sympathetic nervous system and an increase in heartrate [25], while relaxation and calm are associated with activation of the parasympathetic nervous system and a decrease in heartrate [210]. Therefore, it would be expected that if fast music creates a more physiologically arousing response in listeners compared to slow music, this difference would manifest in differences in heartrate.

Generally, studies have supported a trend towards higher heartrate being associated with music of faster tempos than slower tempos [202]. However, the direction of the heartrate change has varied considerably between studies, reflecting the heterogeneity of methodologies. In his review of the literature Koelsch [30] found that music generally increases the heartrate in listeners. However, Krabs et. al [202] report that some studies have found that heartrate increases with fast tempo and decreases with slow music [206, 211], and some have found decreases in heartrate with both slow and fast music [29, 212].

From these results, I expected that hearing even a simple rhythmic auditory stimulus such as a heartbeat will be able to generate changes in physiology. However, the effect of this stimulus on the ANS will depend upon attention levels [203]. Further, I predicted that there would be two effects: one effect that was due to the mere presence of the auditory rhythmic stimulus, and a second effect that was due to the tempo in particular. Given the heterogeneity of methodologies that have been used to study the effects of music on heartrate [30, 202], it is difficult to predict whether the overall effect of the auditory heartbeat will increase or decrease the heartrate. However, if the auditory heartbeat decreases heartrate, it would indicate activity of the parasympathetic nervous system [210] while a systematic increase in heartrate would indicate activity of the sympathetic nervous system [25].

The second effect I was interested in was whether the difference between fast and slow tempos would create relatively faster or slower heartrates in listeners. This would be evidence of a special type of rhythmic entrainment that is discussed more in Section 3.3.4.

3.4.4 Effects of Empathic State on Physiology

Section 3.2 presented an overview of the ways that empathy is part of music and musicking, and Section 3.3 presented routes to empathy through musical emotion. Although much work has connected empathy to music, just one study to date has studied the effects of empathic state manipulation on induced emotions in a controlled study.

To that end, Miu et. al [213] experimentally manipulated the effects of empathy on induced emotion while watching opera. They used a between subjects design with two different listening instructions. In the high-empathy group, participants were instructed to imagine what the performer was experiencing and try to feel it themselves. In the low-empathy condition, participants were instructed to take an objective perspective on the performance.

Researchers found that the high empathy group reported significantly greater felt emotions and their physiological state were coherent to those of the emotion in the music. A similar physiological contagion from performer to audience has also been shown in music performance [214], but this was the first to show that different physiological reactions occur depending upon the empathic state of the listener. They also demonstrated that trait empathy (as measured through the TEQ) was predictive of sadness, wonder and transcendence on the Geneva Music Emotion Scale (GEMS). This result is congruent with the role of empathy and emotional contagion linking recognized and felt emotions [50] but is demonstrated with physiological measures as well.

Compared to [213], my work also leverages physiological methods, namely heartrate. However, instead of a specific "low-empathy" condition, I explored how empathy changed due to different modalities and audio-visual relationships. I also systematically varied one musical variable (tempo) across two levels, which allowed me to clearly determine how this variable impacts empathy. I also report results over significantly more trials, and with significantly shorter exposures (i.e. 20s). I predicted that differences in presentation would manifest in differences in empathy, and these differences would be physiologically differentiable in less than 20s.

CHAPTER 4

THEORY & HYPOTHESES

There are several areas of research that are relevant to the empathic effects of auditory heartbeats. These were framed in terms of applications of heartrate sharing in Chapter 2 and research on music and empathy in Chapter 3. Based upon these prior works, this chapter extends and converges these theories around a set of testable hypotheses. The theoretical bases for these hypotheses are presented in Sections 4.1 and 4.2, where they are referenced in text as H1, H2 and H3 respectively. Section 4.3 concludes the chapter by listing the the hypotheses separated by predictions of changes in empathic state, heartrate (ECG), and the heartbeat-evoked potential (EEG).

4.1 Music & Empathy Research

4.1.1 Empathy

Sections 3.1.1 and 3.1.2 introduce the topic of empathy and its measurement. Some of the major themes related to this work are cognitive and affective components, state versus trait empathy, and also whether empathy extends to abstract acoustic stimuli. I expected that hearing the sound of a person's heartbeat will affect empathy (H1), which can be measured in both cognitive (H1.1) and affective (H1.2) components. Based upon prior research, I further expected that long-term dispositional traits of the participants would correlate with their empathic response (H1.3).

The ability to perceive one's own heartbeat (i.e. "Interoception") has been associated with affect and emotional responsivity (Sec. 3.1.3). Furthermore, differences in interoceptive ability are associated with differences in the Heartbeat-Evoked Potential (Sec. 3.1.5). Although it is not common to hear the heartbeat of another person, I expected that if it could be heard, it will affect listeners' cardiac neurophysiology (H2 & H3). Specifically, I hypothesized there will be physiological entrainment towards the auditory heartbeat tempo (H2.2), and that listener's cardiac cortical processing will be reduced (H3.1).

4.1.2 Music & Empathy

Section 3.2.1 presented evolutionary, neurochemical, and intervention-oriented evidence supporting the important pro-social and empathic functions of music and musicking. A large portion of this evidence comes from research on group musical interactions such as dance, singing and performance. However, the social powers of music may extend beyond group motor synchronization and may be apparent in the act of listening itself. To that end, I expected that listening to even a simple rhythmic stimulus attributed to the physiological state of another person would affect listener's empathic state (H1) and would be accompanied by changes in the listener's physiology (H2), specifically their heartrate. I further predicted that there would be differences in heartrate due to heartbeat tempo, suggesting physiological entrainment (H2.2).

There are many ways that a listener could empathize with music, including through the composer, performer or a "virtual persona" (Sec. 3.2.4). Although empathetic listening may be a relatively common mode of listening in music, to my knowledge, there has been only one study that has manipulated this type of listening in particular [213]. They found evidence that empathy resulted in physiological congruency with the performer's affective expression. To this line of work, I explicitly explored the effects of empathizing with a "virtual persona" by having the participants listen to the heartbeats of an imagined person. I predicted that empathetic listening will appear as physiological entrainment (H2.2), and greater physiological arousal (H2.3).

An important subset of the work on empathy has demonstrated that empathetic listening traits are predictive of listeners' preferences for music (Sec. 3.2.2). From these results, I expected that empathetic traits will also impact responses to my auditory stimulus and would correlate with the empathic response (H1.3).

4.1.3 Music & Emotion

Section 3.3.1 gave an overview of research on musical emotion including some of the most important questions in the field. There are many acoustic features that correlate with musical emotions, and tempo has a fundamental, cross-cultural role in arousal. Unlike musical studies involving complex pieces of music with many co-occurring structural and acoustic features, my study focuses entirely upon the effects of one structural variable: tempo. Because tempo is able to modulate recognized emotions in music, I predicted there will be changes in cognitive empathy due to heartbeat tempo in particular (H1.1).

Although people can recognize emotions in music, it is an entirely different question as to how and why emotions are induced. Section 3.3.2 presented nine possible mechanisms, of which two are empathic: Emotional Contagion (Sec. 3.3.3) and Rhythmic Entrainment (Sec. 3.3.4). Although emerging from different psychological theories, they both have important social dimensions, and reflect a type of "internal mirroring" of the acoustic stimuli. If emotions are actually induced in my study, I predicted there would be changes in affective empathy (H1.2), reflected by their "feeling what the other person was feeling."

Further, as truly induced feelings, I predicted there will be complex associated changes in listeners' physiology (H2). Different factors would produce different physiological states. Due to the acoustic Orienting Response (OR) [215, 216], the onset of auditory heartbeats would produce a decrease in heartrate observable (H2.1). Importantly, if these empathic routes to music emotion are true, I predicted that the listener's heartrate will physiologically entrain to the tempo of the heard heartbeat (H2.2), subject to constraints and lags of the autonomic nervous system [31].

Music can have powerful emotional effects on listener's perception and cognition of visual scenes (Sec. 3.3.5). I leveraged this ability in my sonic design, which is applied to an existing dataset of visual stimuli. As such, I expected that the addition of the heartbeat modality will create a change in the cognitive empathy—the perceived emotion of the imagined person. There will also be changes due to the affective relationship of the heartbeat tempo and the visual stimuli–whether the heartbeat “matches” or “fits” the eyes. In particular, I predicted that incongruent audio-visual stimuli will produce more changes in cognitive empathy than congruent stimuli (H1.1). However, congruent audio-visual stimuli will produce greater affective empathy than incongruent stimuli (H1.2).

4.1.4 Physiological Effects

Section 3.4 presents a variety of work associating music and tempo with changes in the autonomic nervous system, and the heartrate in particular. The auditory heartbeat featured prominently in the uterine auditory environment, and the affective association of tempo and physiological changes would have been learned early in ontogenetic development (Sec. 3.4.1). Because the heartbeat is a rhythmic auditory stimulus resembling the beat of music, I expected to find comparable results as music on heartrate (H2).

A branch of research into the physiological effects of tempo has explored the question of whether the heartrate of listeners will entrain towards the tempo of an auditory (musical) stimulus (Sec. 3.4.3). Although the trend of faster tempos to faster heartrates is supported by the literature, there is some ambiguity as to whether this physiological entrainment occurs in a context of a universal increase or decrease in heartrate that is attributed to other factors, or even if it occurs at all [217]. Within this line of research, my work is unique because I used comparatively short (i.e. 20s) audio samples, varying the samples along just one acoustic dimension (i.e. tempo), and attribute them to the affective state of another person. Based upon the tempo and empathetic listening context, I predicted that there would be physiological entrainment (H2.2).

4.2 Applications of Auditory Heartbeat Sharing

4.2.1 Physiological Signal Sharing

As discussed in Section 2.1.1, fundamental questions for physiological signal sharing (PSS) pertain to its form and effect. For example, what physiological signal should be used and what mediated form should it take? How does perceiving the physiological signals of another person affect interpersonal relationships? Although it will take many years, users and PSS applications to answer these questions, I expect that the heart and heartrate will continue to feature prominently. The heart appears in mainstream PSS applications [77], is a popular trope in emojis [218, 219], and there is a basic cultural metaphor linking the heart and feeling [112].

Much of the prior work on heartbeat sharing has been conducted in real-world scenarios and used verbal and visual representations of heartrate. This work has identified two primary functions of heartrate sharing: heartrate as information, and heartrate as connection. By contrast to this work, I utilized a non-verbal auditory representation of the heartrate, and a controlled laboratory study. However, the two dimensions identified in this prior work are conceptually similar to the notions of cognitive and affective empathy. I hypothesized that hearing a person's heartbeat will change cognitive empathy (H1.1) and increase affective empathy (H1.2).

A subset of this prior research has studied the interpersonal and emotional effects of the *auditory* modality in particular. Their main results are that hearing someone's heartbeat has comparable levels of intimacy as eye contact or being in close physical proximity to them, tempo is the main driver of emotional intensity, and that interpersonal effects require the cognitive attribution of the heartbeat to the viewed person. From these results, I hypothesized that there would be differences in empathy due to (i) the heartbeat and (ii) its tempo. To test for this effect, my experiment design includes trials with auditory heartbeats of slow and fast tempi interspersed with trials of silence. I hypothesized that modality and tempo would cause differences in cognitive (H1.1) and affective (H1.2) empathy.

As shown in previous work, hearing someone's heartbeat has a comparable level of intimacy as direct eye contact [71]. If my measure of affective empathy was correlated with intimacy, I expected that comparing eyes-alone (visual-only) or heartbeat-alone (audio-only) would produce similar levels of affective empathy, and that their combination would produce higher levels of affective empathy than either independently (H1.2).

4.2.2 Biomusic

Section 2.2 presents a continuum of approaches to using sound and music for sharing biosignals. Contemporary applications of biomusic seek successful communication of affective state of the wearer. If these instruments can change the audience's perspective on what the performer is experiencing, or increase their affective connection to them, that particular musical approach may also have merit as an empathic technology ([40], Sec. 2.1.4).

Many biomusic systems use acoustic mappings to convey several physiological variables simultaneously. However, there are cognitive limits to the number of auditory steams that can be followed at once [220]—an important design challenge for auditory display [221]. To this end, I hypothesized that even a simple rhythmic sound (i.e. a heartbeat) could provide enough information to alter cognitive (H1.1) and affective (H1.2) components of empathic state. By comparison to these multiple-variable examples, the association of a simple rhythmic sound to arousal might also be easier to learn and require less cognitive bandwidth to process.

4.2.3 Autism

As discussed in Section 2.3, people with Autism have a reduced ability to use facial expressions, tone of voice, and other common social signals to infer mental state. However, their abilities to engage with music are remarkably unaffected. In fact, music may provide cognitive and affective cues that people with autism can interpret.

An important prospect for my sound design strategy is its application for people with autism or alexithymia. If my experiment showed that auditory heartbeats can change cognitive empathy (H1.1) and increase affective empathy (H1.2), I hypothesize that my results would extend to autistic populations due to the homologous relationship of auditory heartbeat and musical beat. Furthermore, if the auditory stimulus affects physiology (H2), similar physiological state changes might be present in those with autism, including autonomic physiological entrainment (H2.2).

4.3 Hypotheses

Section 4.1 presented current research trends in music, emotion and empathy that are relevant to empathic heartbeat listening. Section 4.2 summarized current findings and theories relating to the applications of auditory heartbeats in affective communication. From these results and theories, I tested the following hypothesis related to changes in empathic state (H1), heartrate (H2) and the heartbeat-evoked potential (H3).

H1 Hearing another person's heartbeat will affect listener's empathic state.

  H1.1 Listener's cognitive empathy will change.

    - The tempo of the auditory heartbeat will serve as an acoustic cue of arousal, changing listeners' perspective on the others' affect.

  H1.2 Listener's affective empathy will increase.

    - The auditory heartbeat will increase connection and intimacy, translating into to higher levels of "feeling what the other was feeling."

  H1.3 Listener traits will impact empathic response.

    - Participants' empathic traits will influence their empathic responses to the auditory heartbeat.

H2 Hearing another person's heartbeat will affect listener's heartrate.

H2.1 Listener's heartrate will decrease.

  - Listeners will have a physiological orienting response (OR) to the acoustic stimuli.

H2.2 Fast heartbeats will be associated with higher heartrates than slow heartbeats.

  - Listening empathically will result in autonomic physiological entrainment to the heartbeat tempo.

H2.3 High affective empathy will be associated with higher heartrates than low affective empathy.

  - Affective empathy will will be characterized by greater physiological arousal.

H3 Hearing another person's heartbeat will change listener's HEP.

H3.1 Listener's heartbeat-evoked potential (HEP) will become more negative.

  - Listening to the heartbeat of another person will decrease attention to one's own heartbeat.

CHAPTER 5

EXPERIMENTAL METHODS

5.1 Introduction

The overall goal of the experiment was to measure empathic-state and neurophysiological change during empathic listening to the perceived auditory heartbeats of another person. This experiment would allow me to test my research hypothesis (see Sec. 4.3)

To that end, I used the Reading the Mind in the Eyes Task (RMET, [134]) to represent the imagined person. This instrument was used because of the prevalence of visual stimuli in current measurements of empathic state (see Sec. 3.1.2), its widespread use as a psychological instrument,[1] also because the RMET has been used in particular for diagnosis of autism and alexithymia [138].

The instrument was administered five times over the course of the study: once its standard form as a pre-trial baseline, and four more times in a modified version (once for each of the four conditions I studied). These conditions varied in terms of modality (i.e. Visual-Only, Audio-Only, Audio-Visual), in terms of congruency (i.e. Audio-Visual Congruent or incongruent), and in terms of tempo (i.e. Fast or Slow auditory heartbeats).

I predicted that perceiving the heartbeat of another person would affect empathic state for the observer, in particular by increasing affective empathy and changing cognitive empathy. I predicted that the modality, congruency and tempo of the stimulus would produce different effects. Furthermore, I predicted that these differences in empathic state would be measurable in the heartrate of observers with 20 seconds of stimulus exposure. I also reasoned that participants would differ in their responses due to static, long-term, dispositional factors.

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[1] There are 4743 citations for the original publication [134] as of November 15, 2019.

5.2 Subject Participation & Consent

5.2.1 Recruitment & Prescreening

Participants in the experiment were students at Georgia Tech in the psychology subject pool (SONA). I posted an advertisement on the SONA website with a description of the experiment, inclusion and exclusion criteria. Participants were eligible if they were between the ages of 18-69 years old, were fluent English speakers and had normal or corrected-to-normal hearing or vision. I informed participants that the experiment would take up to three hours, and that they would be compensated with three SONA credits upon completion.

As part of participation in the study, eligible participants scheduled 10-minute preparation meetings so that I could determine their EEG cap size, test for allergies to the ECG and EEG conductive gels, and to introduce them to the study. At the meeting, I asked the participants to arrive to the study with clean, dry hair free of gels, sprays or other products. If they wore glasses, I asked them to plan to wear their contacts. Because of the length of the study, I also asked that participants to come to the experiment well-rested and recently-fed. I sent a subsequent reminder the day before through text message.

When participants arrived at the study, I reminded the participants that the study would be up to three hours and asked that they begin by using the restroom to avoid interruptions. After coming back, I reintroduced them to the study and gave them a consent form to review. After reading the form and asking any questions they had, they signed the form.

5.2.2 Study Overview

In the first 30 minutes of the study, I outfitted the participants with the ECG and EEG sensors and verified their signal quality. The description of preparing the ECG sensors for recording can be found in Section 5.10, and the description for preparing the EEG cap for recording can be found in Section 5.11. While I minimized the impedance of the EEG sensors, the participants completed the pre-trial survey instruments discussed in Section

5.6. Once these had been completed, and the sensors had been checked for quality, I asked them to put their phone into airplane mode and leave it in their bag for the duration of the study.

The study-portion began by giving subjects a verbal overview and instructions on how the study would commence. The text of this overview and the instructions can be found in Appendix A. Once these were given, I left the room and monitored their progress through a synchronized data file and a realtime audio and ECG signal display. If the ECG sensor came off in the course of the study, I would enter the room at one of the breaks to place it more securely. Otherwise, the participants went through the trials at their own pace. Approximately one-third and two-thirds of the way through the study, I entered the room and offered them the opportunity to stand up and stretch, drink water, and engaged them in brief conversation with the goal of reclaiming their attention levels.

5.3 Audio Stimulus: Heartbeat Sound Model

To precisely control the tempo, variability and loudness of the heartbeat sound, I modelled the sound of a beating heart in the audio and computer music software SuperCollider.[2] The algorithm used a single recorded sample of a heartbeat which I selected after listening to several heartbeat sounds for quality and realism.[3] The selected sample was then further processed in Audacity to remove extraneous noise.

I designed my Supercollider code to trigger this sample repeatedly according to an experimenter-specified BPM. I added small timing and loudness deviations to the sample for added realism. For randomness I used a normal distribution with mean $\mu = 0$ and standard deviation $\sigma = 0.08 * 40/\beta$ where β was the desired heartbeat BPM. These parameters were tuned by ear for perceptual realism and verified by independent observers. The code for controlling the heartbeat sound is available in Appendix C, and the processed sample is

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[2] https://supercollider.github.io/, Retrieved: Dec. 1, 2018.

[3] Chosen Recording: https://freesound.org/people/harrybates01/sounds/254364/, Date Accessed, August 31, 2019. Note that the description of this sample reveals a non-cardiac source.

available on Archive.org.[4]

5.4 Visual Stimulus: Reading the Mind in the Eyes Task

I used visual stimuli from the Reading the Mind in the Eyes test (RMET), originally published in [134].[5] In the test, the participant is asked to infer the affective state of a person after viewing an image of their eyes. The published dataset includes 36 sets of eyes representing male and female genders and various affective states.

Figure 5.1 shows a practice example and the four corresponding affective label choices from the original online test. Figure 5.7 shows the full range of emotional and mental states in the possible answers to each set of eyes. The dataset comes with a supplementary dictionary to assist the participant in cases where a word definition is unknown.

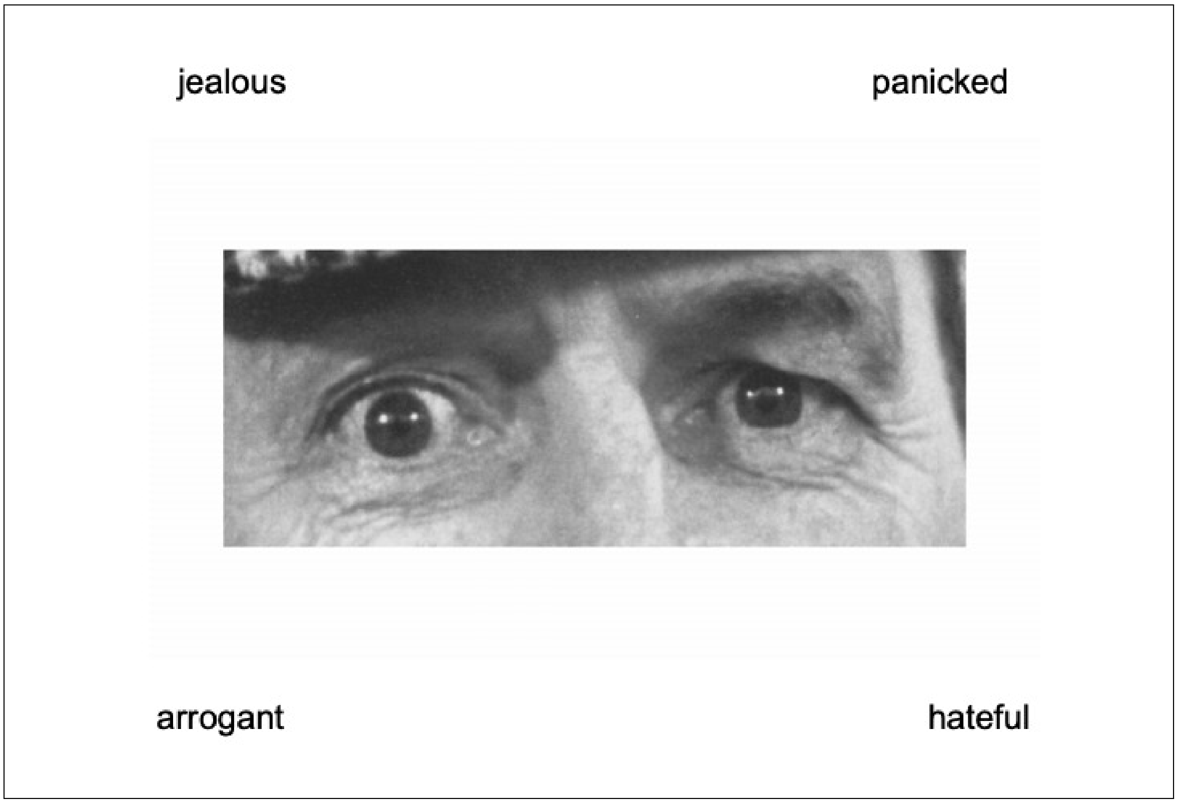

Figure 5.1: A figure showing an example of the original stimuli used in the Reading the Mind in the Eyes task (RMET) [134]. There are 36 sets of eyes in the full experiment.

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[4] Available Online: https://archive.org/details/Empathy-Heartbeat, Date Accessed, August 31, 2019.

[5] Available Online: https://www.autismresearchcentre.com/arc_tests/, Date Accessed: September 1, 2019.

5.5 Response Collection & Synchronization

For the purposes of the test, images of the eyes from [134] were taken from the original test to use as visual stimuli in my stimulus presentation and response collection software, Supercollider. My custom-built experimental interface paired the eyes stimuli with slow or fast heartbeat sounds, collected participant responses, saved the data, and sent synchronizing markers to the LSL program recording the EEG and ECG signals. I made the GUI following a Model-View-Controller paradigm, and the code is freely available on Github.[6]

5.5.1 Cognitive Empathy Question

Each trial began by presenting a random selection from the Reading the Mind in the Eyes task to the participant. The selection comes with a set of eyes and four possible affective labels. The participant needed to answer the question: "What is this person feeling" before they could continue.

In my experiment software, the affective labels appear on buttons that change color when the participant selects them. The original RMET provided a dictionary in case a participant does not know the definition of a word. I put these definitions into "tooltips" that would pop-up if a participant hovered their mouse over a button containing a word. To reduce learning effects, the position of the affect labels was randomized for each trial.

I set the presentation length for the stimulus to be 20 seconds because my previous piloting had shown that heartrate changes would typically occur within 20 seconds of the auditory stimulus presentation. If the participant selected their response early, I asked that they continued to look at the image and/or listen to the heartbeats and imagine what the person is feeling until the stimulus presentation period ended.

Figure 5.2 shows an example of the presentation of Question 1 for a practice trial. The exact instructions given to the participants before the study began can be found in Appendix A.

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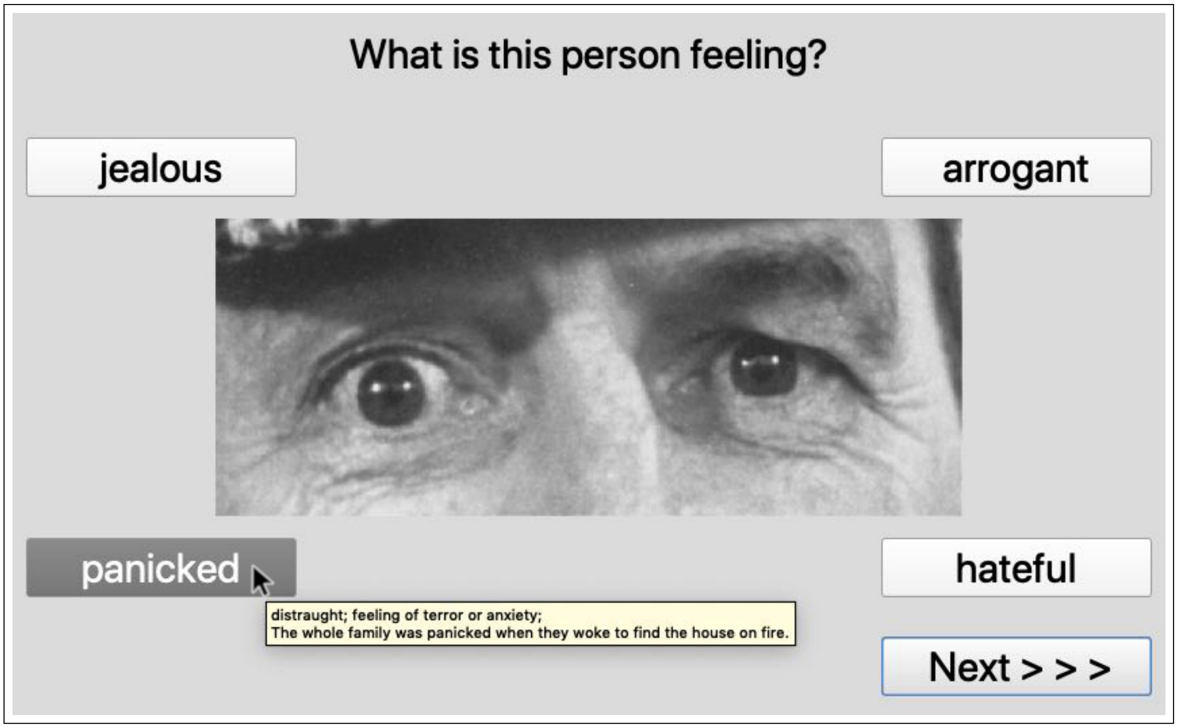
[6] Available online: https://github.com/mikewinters10/Heartbeat-RMET.



What is this person feeling?

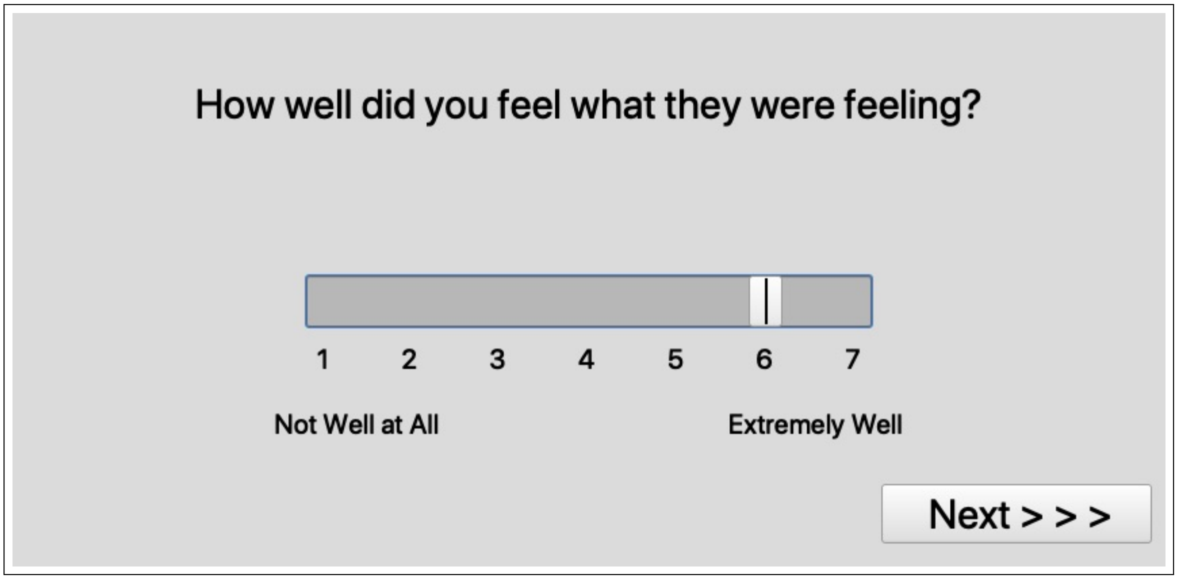
distraught; feeling of terror or anxiety;
The whole family was panicked when they woke to find the house on fire.

Figure 5.2: The cognitive empathy question asked: “What is this person feeling?” The participant needed to select one of four affect labels before they could continue. Hovering the mouse over any word would show a definition. The next button appeared after 20s of stimulus presentation and participant selection.

5.5.2 Affective Empathy Question

After 20 seconds of stimulus presentation and answering the cognitive empathy question, the audio-visual stimulus would end, and the participant would move to the second question. This question asked: “How well did you feel what they were feeling?” and referred to their affective experience during the stimulus presentation. I based this question upon original conceptualizations of empathy as *inner Nachahmung* or inner imitation [222, 128]. Figure 5.3 shows the presentation of the affective empathy question as presented in the Supercollider GUI.

The second question served a second purpose: to return the participant’s heartrate to baseline in preparation for the subsequent trial. After 10 seconds had passed, if the participant had answered the question, the “Next” button would appear allowing the participant to continue. The length of 10 seconds was determined by previous piloting to be the suf-



How well did you feel what they were feeling?

Figure 5.3: The affective empathy question asked: “How well could you feel what they were feeling.” The participant answered on a 7-point scale from “1 - Not Well at All” to “7 - Extremely Well” using a slider that would snap to the corresponding numbers. The next button appeared after 10s of baseline/rest and participant selection.

ficient to return the participant’s heartrate to pre-trial levels. The full instructions given to the participants for answering the Affective Empathy question can be found in Section A.

5.6 Pre-Test Questionnaires

Participants filled out questionnaires and scales to measure latent empathetic traits, personality, musicianship and basic demographics in the 20-30 minutes that it took to apply gel and minimize the impedance of all 64 EEG channels. These questionnaires included the Interpersonal Reactivity Index [131], Toronto Empathy Questionnaire [223], Emotional Contagion Scale [224], Short Big-5 Inventory [225], and the Musical Training, Perceptual Abilities and Active Engagement portions of the Goldsmith Musical Sophistication Index [226]. I also administered the RMET in its standard form as a baseline condition for the cognitive empathy measure.

5.6.1 Measuring Empathic Traits

Researchers have designed many measurement inventories to measure and evaluate empathy over the years [227]. For the purposes of this research, I used two in particular. These were the Interpersonal Reactivity Index (IRI, [131]), and the Toronto Empathy Questionnaire (TEQ, [223]).

The IRI is perhaps the best-known empathy scale and was the first to treat empathy as a multidimensional construct. It was chosen because of its frequency of use and because of its useful subscales which track different components of empathy. The scale includes 28 questions on a five-point scale, with seven questions for each of its four subscales. The four subscales are Fantasy, Perspective Taking, Empathic Concern and Personal Distress. The first two qualify as components of cognitive empathy, and the second two as components of affective empathy.

The TEQ is a relatively new scale and was chosen for the purpose of creating a brief uni-dimensional measurement of empathy. The scale includes 16 five-point questions and has high internal consistency and test-retest reliability.

5.6.2 Measuring the Trait of Emotional Contagion

In addition to these two empathy scales, I used the Emotional Contagion Scale (ECS [224]) as a way of isolating emotional contagion as a specific trait that contributes to my responses and physiological measurements. The ECS includes 15 questions on a four-point scale from “Never” to “Always.” Additionally, it has five separate subscales, one for each of five emotions: Happiness, Love, Fear, Anger and Sadness.

5.6.3 Measuring Personality

To measure personality, I used a 10-item inventory of the Big-5 personality traits [225]. I chose a short questionnaire because they personality measure was provided in the context of many other surveys and I did not want to burden the participant with too many questions. Nevertheless, this measure provided scores for Extraversion, Agreeableness, Conscientiousness, Emotional Stability and Openness to Experience. The survey includes two questions designed to measure each trait.

5.6.4 Measuring Musical Sophistication

Because the study relies to a large degree on listening, I reasoned that there might be differences in the behavioral and physiological responses due to musical experience. Thus, I also administered a short musical sophistication survey based upon the Gold-MSI Musical Sophistication Test [226]. The test is designed to tease out multiple latent variables contributing to musical sophistication. For the sake of brevity, I focused on Musical Training, Perceptual Abilities and Active Engagement.

5.6.5 Baseline Reading the Mind in the Eyes Task

In addition to the empathy, personality and musical sophistication surveys, participants also completed the Reading the Mind in the Eyes Task (RMET). Unlike the experiment, this baseline presentation of the RMET was administered in its unmodified form: the order of the eyes was not randomized, there were no heartbeats, and participants answered each question at their own pace [134]. The affective labels that participants chose was then used as a baseline score for my subsequent analysis of changes in Cognitive Empathy due to my experimental conditions (Sec. 6.3).

5.6.6 Pre-Trial Survey Flow

The ordering of the surveys was partially randomized in order to remove any ordering effects. Each participant began with simple demographics including their gender, ethnicity, age, and self-reported English fluency. Then they completed the empathy surveys or the personality measure, and the order of these was randomized for each participant. Furthermore, within the empathy surveys, the order of the IRI, ECS and TEQ were also randomized. After, completion, they moved to the RMET, and finally to the musical sophistication surveys. The order of these three surveys were also randomized for each participant. Figure 5.4 displays the pre-trial survey flow graphically.

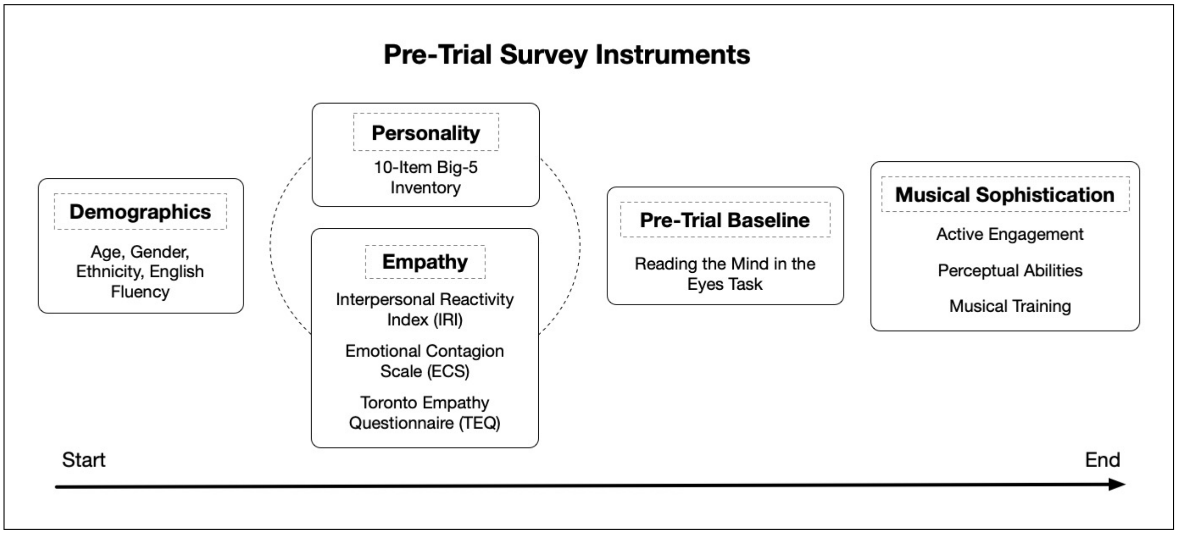


Figure 5.4: The survey flow of the Pre-Trial portion of the experiment. It includes basic demographics, empathy trait questionnaires, a short Big-5 personality test, musical sophistication surveys, and a baseline test of the RMET.

5.7 Conditions & Trial Flow

The final experiment contained 144 trials, one modified RMET for each of four conditions. Each trial contained 20 seconds of stimulus presentation where they answered the cognitive empathy question. This was followed by 10 seconds without stimulus where they answered the affective empathy question. Figure 5.5 displays the temporal flow of each trial graphically.

The four conditions were Visual-Only, Audio-Only, Audio-Visual Fast and Audio-Visual Slow. These conditions appeared 36 times in the experiment (one for each of the 36 trials in the RMET) but were randomly distributed in the trials. The ordering of the RMET was only partially randomized because I wanted the individual trials in the RMET to appear in their entirety before repeating. A diagram visualizing the trial ordering is provided in Figure 5.6.

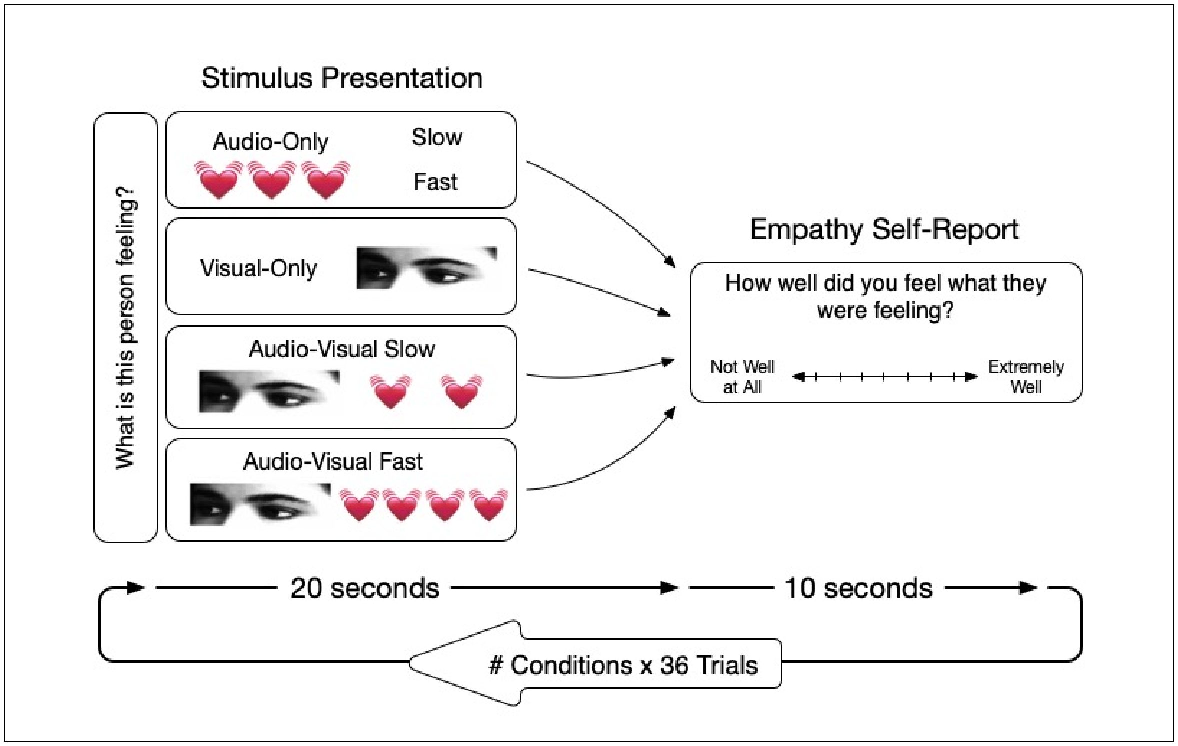


Figure 5.5: The temporal flow of each trial. The trial begins with 20 seconds of stimulus presentation where the participant answers the cognitive empathy question. The trial ends with 10 seconds without stimulus where the participant answered the affective empathy question.

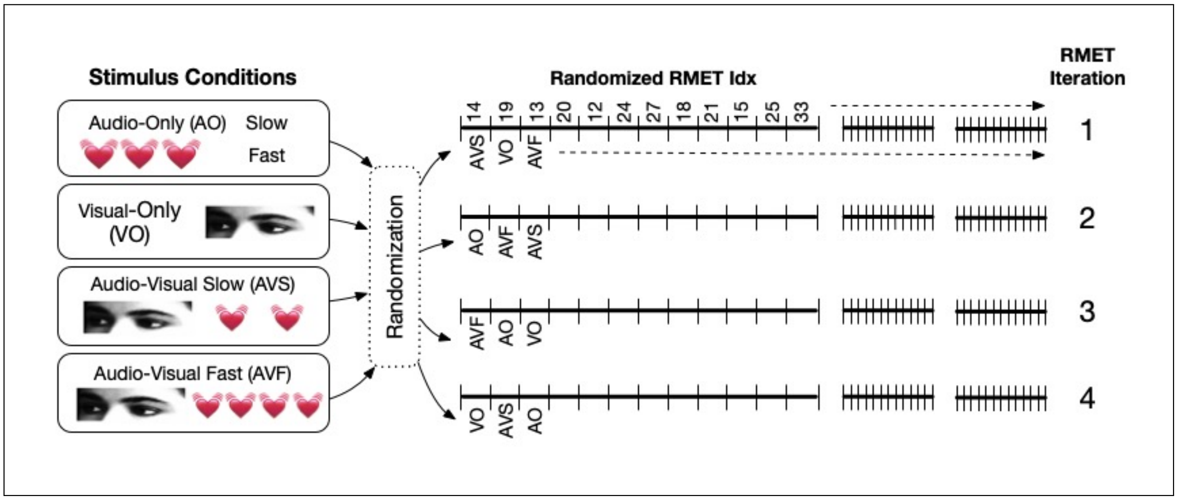


Figure 5.6: A diagram of the trial ordering in the experiment. Four randomized iterations of the 36 RMET trials were presented in sequence and paired with one of the four conditions: Audio-Only, Visual-Only, Audio-Visual Slow, and Audio-Visual Fast. These 144 trials were grouped into 12 blocks of 12 trials.

Table 5.1: A table representing the distribution of the 144 trials of the experiment according to their modality, tempo and congruency.

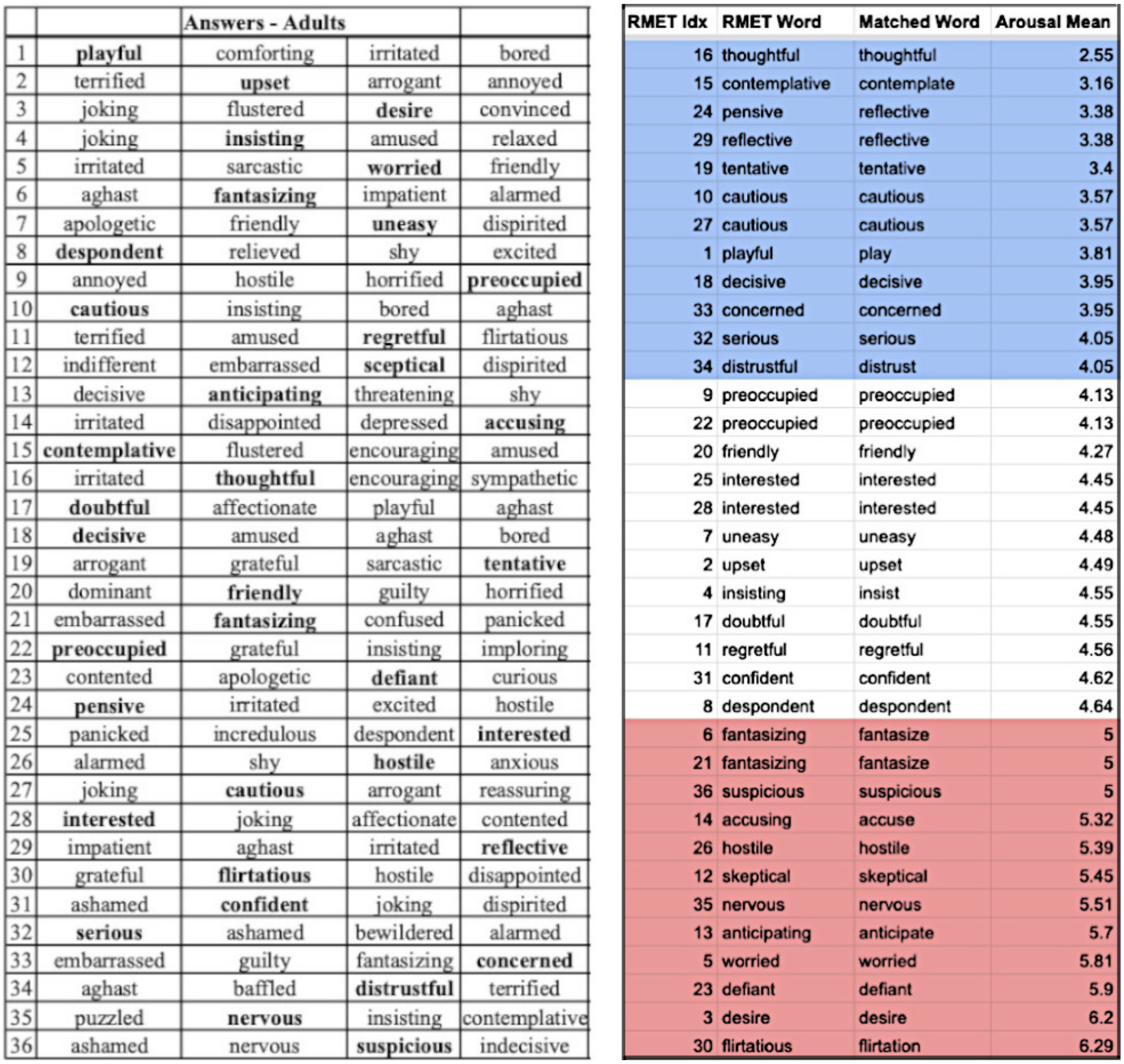
Num. Trials	**Modality**	**Tempo**	**Congruency**
36	Visual-Only	-	-
18	Audio-Only	Slow	-
18	Audio-Only	Fast	-
12	Audio-Visual	Slow	Incongruent
12	Audio-Visual	Slow	-
12	Audio-Visual	Slow	Congruent
12	Audio-Visual	Fast	Incongruent
12	Audio-Visual	Fast	-
12	Audio-Visual	Fast	Congruent

I used these conditions to analyze the responses according to three independent variables: modality, tempo and congruency. I tested effects of modality by comparing the responses from Visual-Only, Audio-Only and Audio-Visual trials. I tested the effects of tempo by comparing responses to Slow and Fast heartbeat stimuli. Because the Audio-Only condition had only 36 trials, I assigned a random but equal distribution of Fast and Slow heartbeats. I tested congruency using the implied arousal of the eyes, as discussed in Section 5.7.1. Table 5.1 shows the number of trials associated with each condition.

5.7.1 Congruent & Incongruent Stimuli

The experiment associated slow and fast heartbeat tempos (i.e. 40BPM and 140BPM) with each set of eyes in the RMET task. However, I reasoned that certain eyes would be a closer “fit” to fast or slow heartbeats, depending upon their visual affect. For example, the “thoughtful” eyes would be better associated with a slow heartbeat than a fast heartbeat, and “panic” would be better associated with a fast heartbeat than a slow heartbeat. I therefore further separated the Audio-Visual trails into “Congruent” and “Incongruent” sets.

To determine the effect of Audio-Visual congruency on empathic state, the 36 RMET visual stimuli were organized into three groups based upon their associated arousal level (i.e. low, medium, and high arousal). Each group had an equal number of stimuli—12 each. Using these categories, I formed a group of "congruent" Audio-Visual stimuli by pairing slow heartbeats with the low arousal RMET group and fast heartbeats with high arousal RMET group. I formed a group of "incongruent" Audio-Visual stimuli by pairing slow heartbeats with eyes in the high arousal RMET category, and fast heartbeats with eyes in the low arousal RMET category. Figure 5.7 displays the grouping of answers in the RMET into low, medium and high arousal.



		Answers - Adults		
1	**playful**	comforting	irritated	bored
2	terrified	**upset**	arrogant	annoyed
3	joking	flustered	**desire**	convinced
4	joking	**insisting**	amused	relaxed
5	irritated	sarcastic	**worried**	friendly
6	aghast	**fantasizing**	impatient	alarmed
7	apologetic	friendly	**uneasy**	dispirited
8	**despondent**	relieved	shy	excited
9	annoyed	hostile	horrified	**preoccupied**
10	**cautious**	insisting	bored	aghast
11	terrified	amused	**regretful**	flirtatious
12	indifferent	embarrassed	**sceptical**	dispirited
13	decisive	**anticipating**	threatening	shy
14	irritated	disappointed	depressed	**accusing**
15	**contemplative**	flustered	encouraging	amused
16	irritated	**thoughtful**	encouraging	sympathetic
17	**doubtful**	affectionate	playful	aghast
18	**decisive**	amused	aghast	bored
19	arrogant	grateful	sarcastic	**tentative**
20	dominant	**friendly**	guilty	horrified
21	embarrassed	**fantasizing**	confused	panicked
22	**preoccupied**	grateful	insisting	imploring
23	contented	apologetic	**defiant**	curious
24	**pensive**	irritated	excited	hostile
25	panicked	incredulous	despondent	**interested**
26	alarmed	shy	**hostile**	anxious
27	joking	**cautious**	arrogant	reassuring
28	**interested**	joking	affectionate	contented
29	impatient	aghast	irritated	**reflective**
30	grateful	**flirtatious**	hostile	disappointed
31	ashamed	**confident**	joking	dispirited
32	**serious**	ashamed	bewildered	alarmed
33	embarrassed	guilty	fantasizing	**concerned**
34	aghast	baffled	**distrustful**	terrified
35	puzzled	**nervous**	insisting	contemplative
36	ashamed	nervous	**suspicious**	indecisive

RMET Idx	RMET Word	Matched Word	Arousal Mean
16	thoughtful	thoughtful	2.55
15	contemplative	contemplate	3.16
24	pensive	reflective	3.38
29	reflective	reflective	3.38
19	tentative	tentative	3.4
10	cautious	cautious	3.57
27	cautious	cautious	3.57
1	playful	play	3.81
18	decisive	decisive	3.95
33	concerned	concerned	3.95
32	serious	serious	4.05
34	distrustful	distrust	4.05
9	preoccupied	preoccupied	4.13
22	preoccupied	preoccupied	4.13
20	friendly	friendly	4.27
25	interested	interested	4.45
28	interested	interested	4.45
7	uneasy	uneasy	4.48
2	upset	upset	4.49
4	insisting	insist	4.55
17	doubtful	doubtful	4.55
11	regretful	regretful	4.56
31	confident	confident	4.62
8	despondent	despondent	4.64
6	fantasizing	fantasize	5
21	fantasizing	fantasize	5
36	suspicious	suspicious	5
14	accusing	accuse	5.32
26	hostile	hostile	5.39
12	skeptical	skeptical	5.45
35	nervous	nervous	5.51
13	anticipating	anticipate	5.7
5	worried	worried	5.81
23	defiant	defiant	5.9
3	desire	desire	6.2
30	flirtatious	flirtation	6.29

Figure 5.7: The answers to the RMET sorted into three arousal groups according to the arousal ratings provided by [228]. There are 12 eyes in each group. The low and high-arousal groups were used for analysis by audio-visual congruency.

Although it is possible to quantify the emotion in each set of eyes based upon their visual content, at the time of this research, there were no available validated ratings.[7] In lieu of creating a validated dataset of emotion ratings for each set of eyes, I used a validated measure based upon the affective content of the emotion label. The chosen dataset contains ratings of arousal, valence and dominance for almost 14,000 words [228]. As a result of this large size, all of the correct labels for the RMET were available, either exactly (78%), or in close approximation (22%, e.g. play → playful, fantasize → fantasizing). Each of the 36 emotion labels had been rated for these three affective dimensions by between 20 and 45 people ($\mu = 25.25$). After associating each word with its mean arousal rating, the words were divided into three equal groups based upon their arousal rating (i.e. low, medium, high). More information about the arousal ratings including the standard deviation and the number of raters, and the associated word in the RMET can be seen in Appendix B.

5.8 Hardware Setup

The BrainVision's ActiChamp amplifier was used to synchronize EEG, ECG and Audio signals. The listener's heartrate was recorded using BrainVision's BIP2AUX Bipolar ECG amplifier as discussed in Section 5.10. The listener's EEG was recorded using a 64-channel active electrode array as discussed in Section 5.11. A specialized audio converter was used to convert the audio-signal into a form that could be input into one of the auxiliary ports of the ActiChamp. Figure 5.8 shows the full hardware setup.

5.9 Audio Recording & Synchronization

I recorded what the participant heard by sending a copy of the participant's audio signal into one of the auxiliary inputs of the ActiChamp EEG amplifier. This procedure allowed

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[7] Contemporary computer Vision systems can detect faces in images and use facial features to quantify the emotion present. However, these were not useable because they were unable to detect a face in any of the RMET images. This detection problem maybe be due to the fact that the RMET images crop out all parts of the faces except the eyes.

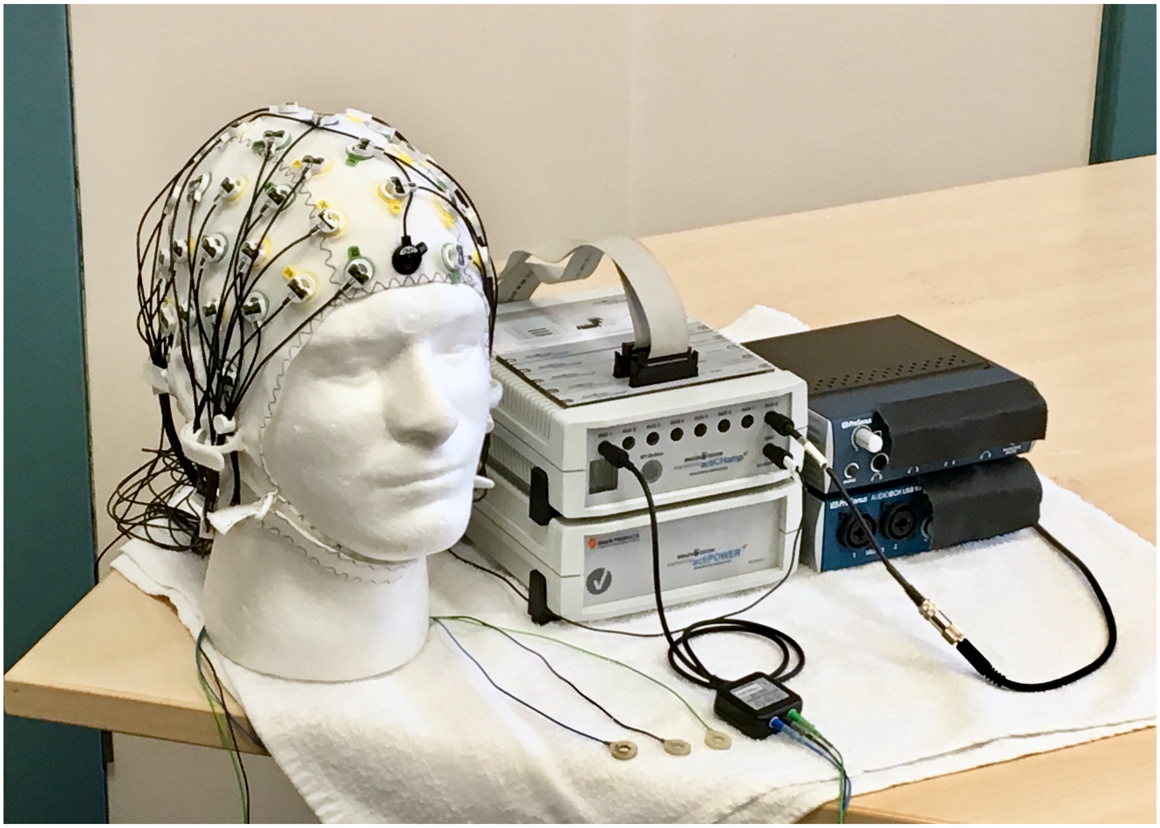

Figure 5.8: A photograph of the hardware setup including a 64-channel EEG cap, sensors, EEG amplifier, BIP2Aux ECG amplifier, ECG leads, and audio interface and headphone amplifier.

for straightforward audio-recording that was guaranteed to be synchronized with the ECG and EEG.[8]

Before reaching the amplifier, the Supercollider audio went to an external audio interface, which served to split the signal into two parts. One signal went to the ActiCHamp amplifier for recording, and the other part went to an external headphone amplifier. The headphone amplifier boosted the volume of the signal and also allowed the participant to set a comfortable listening level that was separate from the version sent to the ActiChamp for recording and synchronization.

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[8] The method used was later found to be susceptible to voltage surges. BrainVision's StimTrak with audio-converter should be used instead.

5.10 ECG Measurement

I placed the leads for the ECG according to Figure 5.9. I positioned the positive lead on the upper right chest, the ground lead symmetric to the positive lead on the upper left part of the chest, and the negative electrode directly downwards from the ground lead on the last rib.

I took special care to ensure the participant's privacy but also to have a correct and secure placement of the three electrodes on the chest. I first trained the participant how to put the electrodes on themselves, and then left the room until they were correctly placed.

To train the participant on the placement of the ECG electrodes, I showed each participant how to position the three sensors and recognize a good signal. I began by pointing to the correct locations on my own chest, and then asked the participant to point on their chest to where the three sensors would be placed. I also directed them to a diagram on the wall with color-coded circles representing the color of the three leads they were going to place, and a second figure below it which showed what a strong ECG signal looked like (See Fig. 5.9). Prior to the participant's arrival, the BrainVision Recorder had been set up to show a realtime signal display of the ECG signal, and so the participant could know when they had a good ECG signal by checking on the diagram.

After the participant finished placing the sensor, they knocked on the door signaling that they had finished. I then verified that they had a good ECG signal and asked the participants to move their arms around to ensure that the sensors were securely affixed.

5.11 EEG Measurement

5.11.1 Apparatus & Acquisition

I used the BrainVision ActiChamp with 64 channels for EEG recording. The 64 active electrodes were placed in locations according to the international 10-20 system [229]. Ground was placed on the forehead, and Reference was placed at FCz. Figure 5.10 shows the full

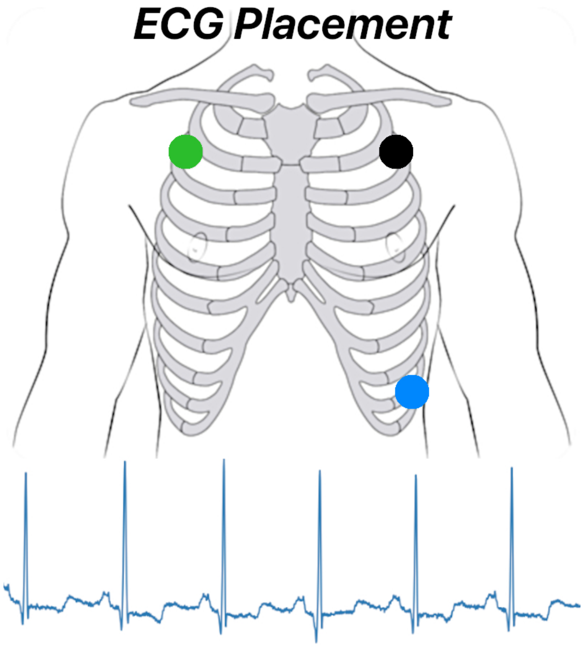

Figure 5.9: A figure of the diagram the participants used to place the sensors on their chest in the proper places and know if they were able to get good quality signal.

sensor placement map.

I used BrainVision Recorder to interface with the amplifier, minimize impedance levels, record the data locally, and stream it to LabStreamingLayer using BrainVision's Remote Data Access (RDA) client.

LabStreamingLayer is freely available software that assists with the realtime acquisition, synchronization, recording, and viewing of multiple heterogeneous data streams [230].[9] I used it to synchronize the custom-built experimental software with data from the ActiChamp amplifier. The final data file was in the extensible data format (XDF), which is an available import format in EEGLAB.

5.11.2 Skin Preparation & Cap Placement

To prepare the subject for EEG application, I used a hard-bristled brush to scrape off any dead skin on their scalp. I demonstrated a circular scraping pattern with the brush and then asked if the participant would like to do it themselves, or if they would like me to do it for

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[9] Freely Available: https://github.com/sccn/labstreaminglayer/wiki, Date Accessed, August 31, 2019.

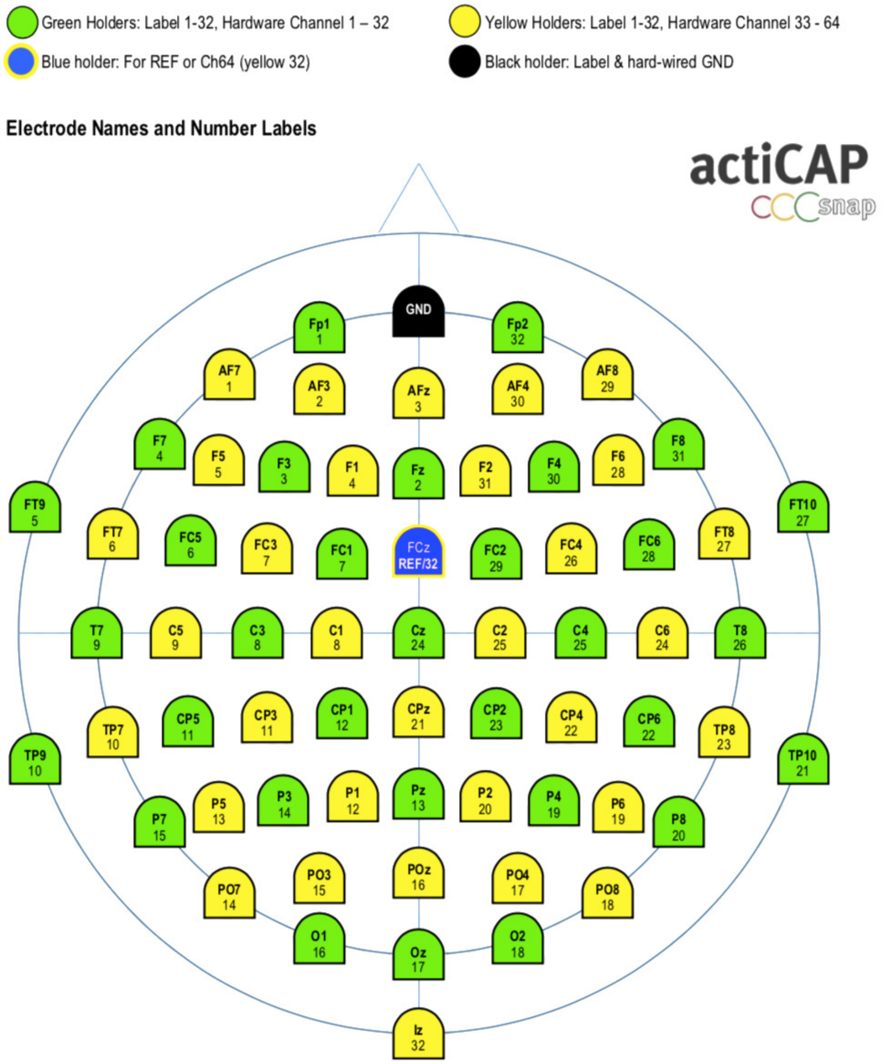

Figure 5.10: A figure showing the 64-channel electrode placement used in the experiment.

them. In all cases, I gave extra attention to removing dead skin from the central electrodes, especially FCz (Reference).

Following this preparation, I provided the participant with a cotton ball soaked with isopropyl alcohol, and instructed them to apply it to their forehead, upper sides of their face, and skin regions behind the ears. The alcohol removed any oils or other contaminants that were on their skin and helped get a better recording for those sensors.[10]

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[10] In previous experiments, I lightly applied sandpaper on the regions of skin first to remove dead skin before isopropyl alcohol treatment. For this experiment, I decided not to do this, but also experienced difficulty reaching proper impedance for certain participants. Given the importance of the ground electrode in getting good signal (which is on the forehead), I would personally recommend continuing light abrasion in the future.

After the subject's skin was prepared, I used a tape measure to locate the central location of their head. First, I measured halfway from nasion to inion, and made a blue mark at the halfway point. Then I turned the measurement 90 degrees and measured the distance between the two ears, placing a second blue dot at the halfway point where it intersected with line of the first blue mark.

The cap was then put on such that the first sensor to make contact was Cz, at the precise location of the blue mark. I then had the participant provide me with their left index finger, which I positioned on that sensor. While the participant held that sensor still, I pulled the cap down, stretching it so that all of the sensors reached their proper location, and making sure it was centered. At this point, I instructed the participant that it was okay to remove their finger and start the pre-test questionnaires.

5.11.3 Minimizing the Impedance

I used BrainVision Recorder's built-in impedance checker to minimize the impedances of the 64 active EEG sensors. For each sensor, I applied gel to build a column between the participant's skin and the sensor. I first lightly abraded the skin and move hair out of the way using a plastic syringe. I then applied gel and pushed down on the sensor in order to increase contact with the gel that was present. I performed this procedure for all 64 sensors, applying more gel as needed until I reached an impedance below 25kOhms.

CHAPTER 6

BEHAVIORAL CHANGES IN EMPATHIC STATE

6.1 State Dependent Variables

As discussed in Section 5.5, each trial of the experiment included two behavioral measurements designed to measure cognitive and affective components of transient empathic state. These questions were:

1. The participants' response to the question, "What is this person feeling?" Their answer was one of four labels associated with each set of eyes in the RMET.
2. The participants' response to the question, "How well could you feel what they were feeling?" Their answer took the form of an integer on a seven-point Likert scale from "1 - Not well at all" to "7 - Extremely Well."

From these two questions, I extracted two dependent variables:

RMET Change Whether they changed their response to the first question relative to their pre-trial baseline selection.

Feeling Strength Z-Score Their answer to the second question standardized across all of that participant's trials such that $\mu = 0$ and $\sigma = 1$.

6.2 Independent Variables & Statistical Analysis

As presented in Chapter 4, my primary research questions and hypotheses relate to the effects of auditory heartbeats on listeners' empathic state and neurophysiology. However, my experiment design allows for a much more nuanced multimodal analysis including effects of modality, tempo and congruency. Modality refers to whether or not the heartbeat was present (i.e. Visual-Only vs. Audio-Visual), or if it appeared independent of a visual stimulus (i.e. Audio-Only). Tempo was either Slow or Fast but appeared in both Audio-Only and Audio-Visual cases, allowing me to study its interaction with modality (i.e. Modality x Tempo). Congruency was only applicable to the Audio-Visual condition and was either Congruent or Incongruent depending on whether the eyes matched the heartbeat tempo. Because this variable was nested inside of tempo, I also studied its interaction (i.e. Tempo x Congruency).

The multimodal structure of my independent variables involves nesting and empty cells. To apply statistical analysis, my approach was to partition the overall analysis for each dependent variable into sub-analyses without empty cells and divide the significance level for the Type-I error rate by the number of analyses (i.e. $\alpha = 0.05/3$). Figure 6.1 shows the partitions for affective empathy and cognitive empathy.

6.3 Change in Cognitive Empathy

I designed the first question to compare the change in participant's perspective on what the imagined person was experiencing (i.e. cognitive empathy). For each trial, their response was compared to their response in the pre-trial baseline. I hypothesized that hearing someone's heartbeat would change the participants' perspective on what that person was experiencing relative to silence.

My approach to analyze the differences attributable to the auditory heartbeat was to use an independent pre-trial baseline measurement. As discussed in Section 5.7, there are many differences between my experiment and the original RMET. My experiment randomized the ordering of the RMET, required that the participants wait for 20 seconds before continuing, and included repetitions of the same set of eyes in different audio conditions. Thus, the difference between my "Visual-Only" condition and this baseline approximates the variation in responses due to the experiment design, and any additional differences in other conditions could be attributed directly to the auditory stimulus.

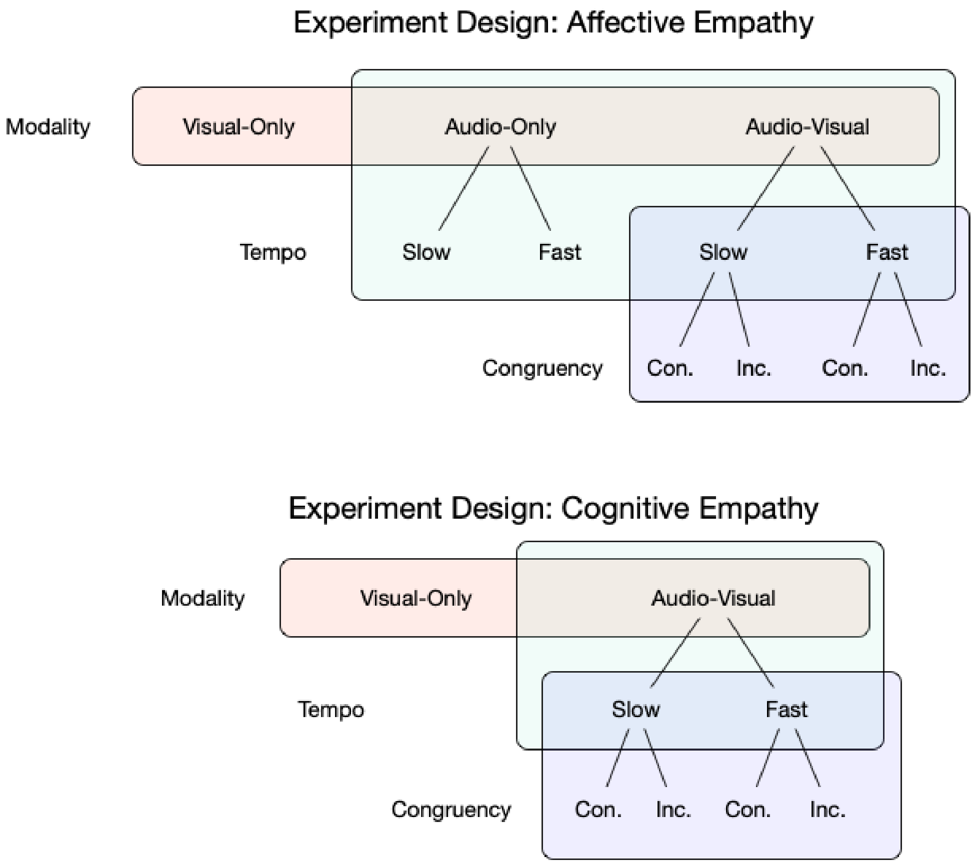

Figure 6.1: My experiment designs using my three nested variables. To handle missing cells, I formed complete sub-analyses, and increased the significance level for my experiment-wide Type-I error-rate by a factor three (i.e. $\alpha = 0.017$). Because changes in the RMET Change variable leveraged the visual stimulus, I excluded the Audio-Only condition from the analysis of cognitive empathy.

For each set of eyes in each of the stimulus conditions, I compared the participant's response to their answer in the pre-trial baseline. If the response was the same, I assigned a zero (0) to the RMET Change variable for that trial representing "No Change." If the participant's response was different, I assigned a one (1) to the RMET Change variable for that trial representing "Change." Because the visual stimuli was required for the comparison to pre-trial baseline, trials from the Audio-Only conditions were excluded. Further, because of a technical error, only 20 of the 27 participants received the pre-trial baseline.[1]

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[1] There were no statistically significant differences between these two groups in their subsequent responses to either of the two empathic state questions.

Using this procedure, every participant contributed 108 samples for analysis for a total of 2160 samples. Because the dependent variable in this case was binary, I applied logistic regression and the Wald χ^2 Test to determine if my explanatory variables were significant, and the odds-ratio (Exp(B)) to determine the likelihood that a participant would change their selection based on that variable.

6.3.1 Effect of Modality

Based upon prior research, I hypothesized that adding the sound of heartbeat would change participants' cognitive empathy (H1.1). In my experiment, this would mean that trials with auditory heartbeats would be more likely to result in a change in participants' selected emotion label than trials without a heartbeat.

Because my dependent variable is binary, a simple logistic regression was calculated to predict the RMET Change variable based upon Visual-Only (N = 720) or Audio-Visual (N = 1440) modality. A significant regression was found with χ^2 = 14.074, $df = 1$, Exp(B) = 1.207, $p < 0.001$, meaning that modality was a significant predictor of the RMET Change variable. Participants were 21% more likely to select a different emotion label when they heard the imagined person's heartbeat. This means that hearing someone's heartbeat had the effect of changing participants' perspectives on what the imagined person was experiencing (i.e. their cognitive empathy). Furthermore, this rejects the null hypothesis for H1.1—that the addition of auditory heartbeats would not change affective empathy. Figure 6.2 displays the proportion of changes in the RMET selection from baseline in the Visual-Only and Audio-Visual Conditions.

6.3.2 Effect of Tempo

My experiment design allowed me to test if the tempo of the auditory heartbeat resulted in differences in participants' selected emotion label. This would mean that the change in cognitive empathy attributable to auditory heartbeats was modulated by heartbeat tempo, with

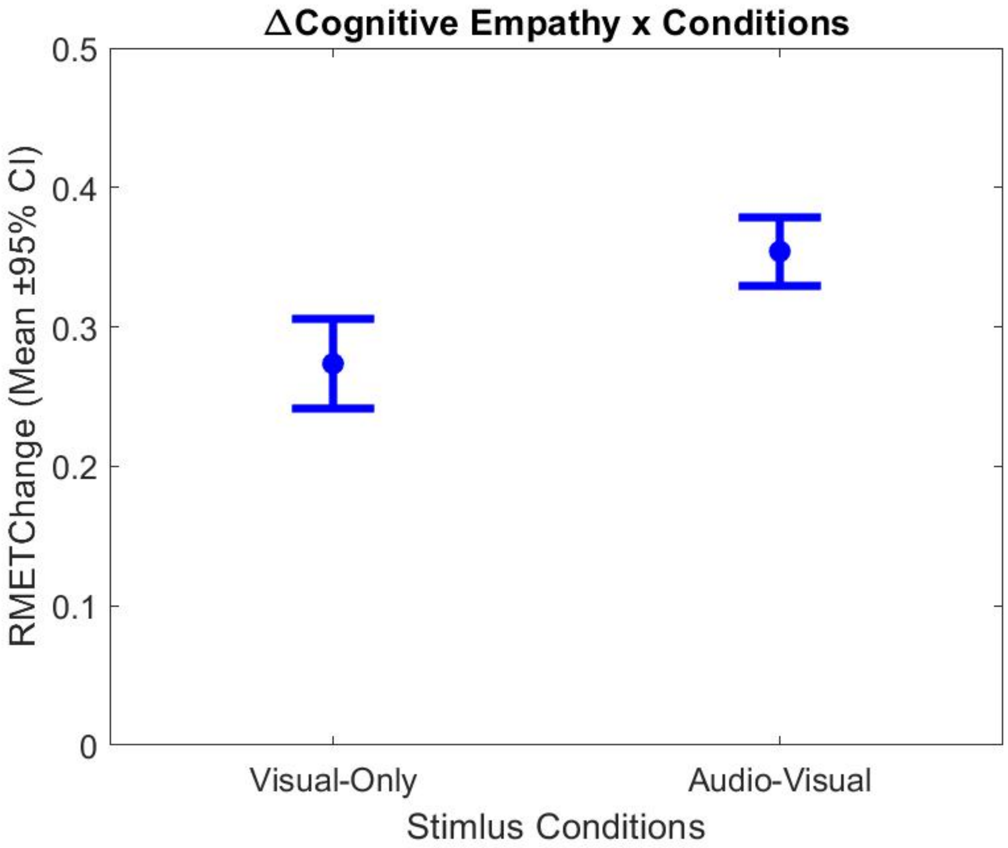

Figure 6.2: A comparison of the proportion of changes in the RMET selection from baseline for the Visual-Only and Audio-Visual conditions. The error bars represent the 95% confidence interval around the mean.

Slow or Fast heartbeats creating more or less changes in listeners' affective perspective.

Because my dependent variable is binary, a simple logistic regression was calculated to predict the RMET Change variable based upon a whether the auditory heartbeat was Slow (N = 720) or Fast (N = 720). A significant regression was found with χ^2 = 9.536, $df = 1$, Exp(B) = 1.406, $p = 0.002$, meaning that tempo was a significant predictor of the RMET Change variable. This means that listener's cognitive empathy was sensitive to the difference in tempo between Slow or Fast heartbeats. Participants were 41% more likely to select a different emotion label when they heard a Fast heartbeat than when they heard a Slow heartbeat. Figure 6.3 displays the proportion of changes in the RMET selection from baseline in the Audio-Visual Slow and Audio-Visual Fast trials.

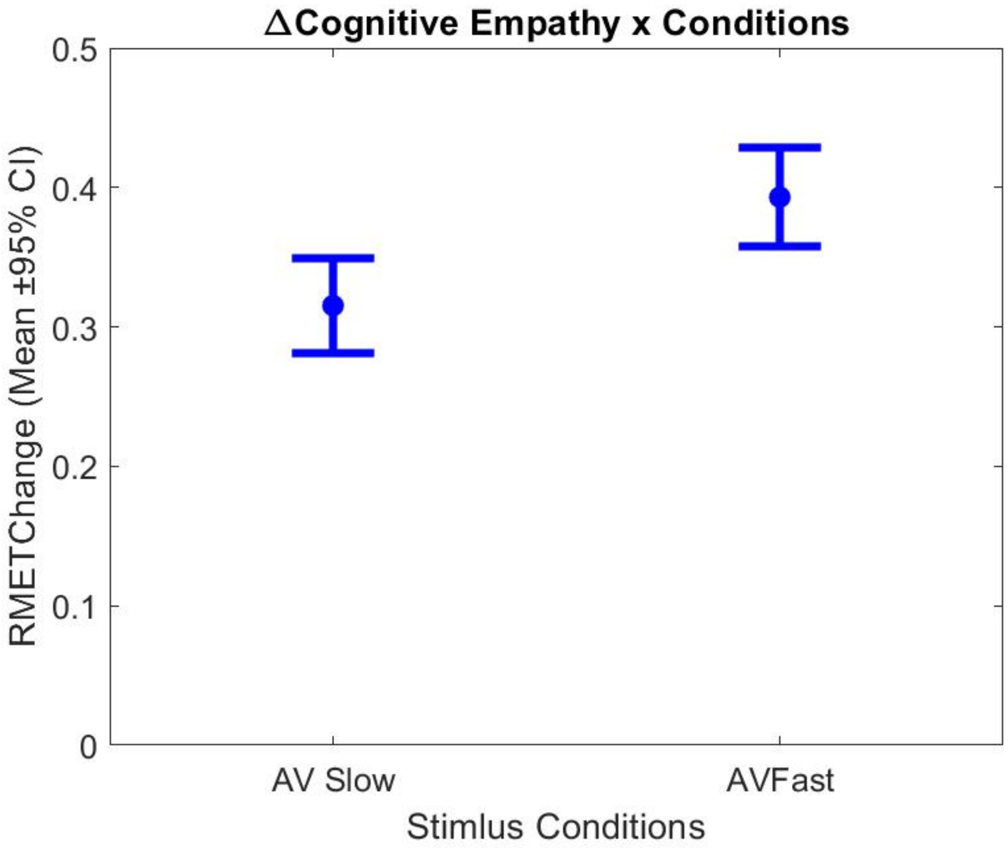

Figure 6.3: A comparison of the proportion of changes in the RMET selection from baseline for the Audio-Visual Slow and Audio-Visual Fast conditions. The error bars represent the 95% confidence interval around the mean.

6.3.3 Effect of Congruency

My experiment design also allowed me to test whether the affective congruency (“match”) between the tempo of the auditory heartbeat and the affect present in the visual eyes stimuli would effect cognitive empathy. If so, this would mean that listeners’ perspectives on the what the other person was experiencing depended on the affective relationship between the auditory heartbeat tempo and the visual affect.

Because my dependent variable is binary, a simple logistic regression was calculated to predict the RMET Change variable based upon whether the Audio-Visual stimuli were Incongruent (N = 480) or Congruent (N = 480). Because congruency was nested in tempo, I first included tempo in my regression model, but found it was not significant and subsequently removed it. In the new model, a significant regression was found with χ^2 = 10.612, df = 1, Exp(B) = 1.564, $p = 0.001$, meaning that congruency was a significant predictor of the RMET Change variable. Participants were 56.4% more likely to change their emotion label when the tempo of the heartbeat did not match the emotion in the eyes. This means that participants incorporated both audio and visual affective content into their decisions, and that affective mismatch created more changes in cognitive empathy. Figure displays the proportion of changes in the RMET selection from baseline in Audio-Visual Congruent and Incongruent stimuli.

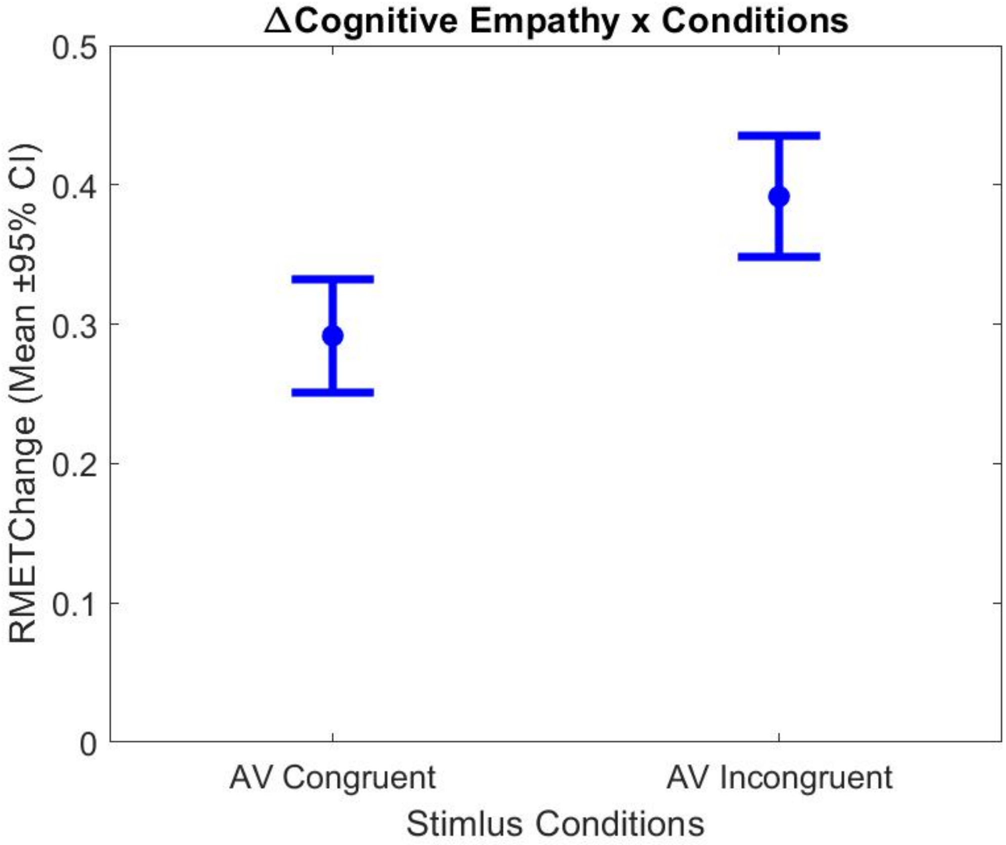

Figure 6.4: A comparison of the proportion of changes in the RMET selection from baseline for the Audio-Visual Congruent and Audio-Visual Incongruent conditions. The error bars represent the 95% confidence interval around the mean.

6.4 Increase in Affective Empathy

The second question was "How well did you feel what they were feeling?" I used this question to quantify the strength of participants' affective empathy with the imagined person. This question is answered through self-report on a seven-point Likert scale, but I wanted to compare the responses across all participants, so I first standardized each participant's responses individually using the z-score. The z-score for each trial was calculated by applying the following formula:

$$z(x) = \frac{x - \mu}{\sigma} \tag{6.1}$$

Where μ is the mean response for the participant across all 144 trials, σ is the standard deviation of the participant's responses across the 144 trials, x is the participant's response for a given trial, and $z(x)$ is the z-score for that trial. This derived dependent variable was called "Feeling Strength Z-Score." To test if the Feeling Strength Z-Score was statistically different in my conditions, I applied a General Linear Mixed Model (GLMM) [231]. This is a modern univariate approach that generalizes a variety of models into one single model with both random and fixed factors [232]. In my analyses, I treat participants as a random factor, and explicitly model the factors of interest.

6.4.1 Effect of Modality

Based upon previous research, I hypothesized that hearing the sound of a person's heartbeat would increase participants' affective empathy (H1.2). In my experiment this would mean that trials with an auditory heartbeat would have greater self-reported Feeling Strength Z-Score than trials without heartbeats.

My experiment design offered three modality conditions: Visual-Only, Audio-Only and Audio-Visual. I applied a GLMM to compare the mean Feeling Strength Z-Score for these groups and found a significant effect of modality on the Feeling Strength Z-Score [F(2,

52) = 5.46, $p = 0.007$]. This rejects the null hypothesis for H1.2—that the auditory heartbeat would not have an effect on listeners' affective empathy. When I performed multiple comparison tests using a Bonferroni correction, I found that the Audio-Visual condition produced significantly higher ratings than the Visual-Only condition ($p < 0.001$) and the Audio-Only condition ($p < 0.001$). Furthermore, there was no statistically significant difference between the Visual-Only and Audio-Only conditions. This means that the increase of empathy was not due to the audio alone, but rather due to the association of the auditory heartbeat with the eyes of the imagined person. Figure 6.5 displays the means and 95% confidence intervals for these conditions graphically.

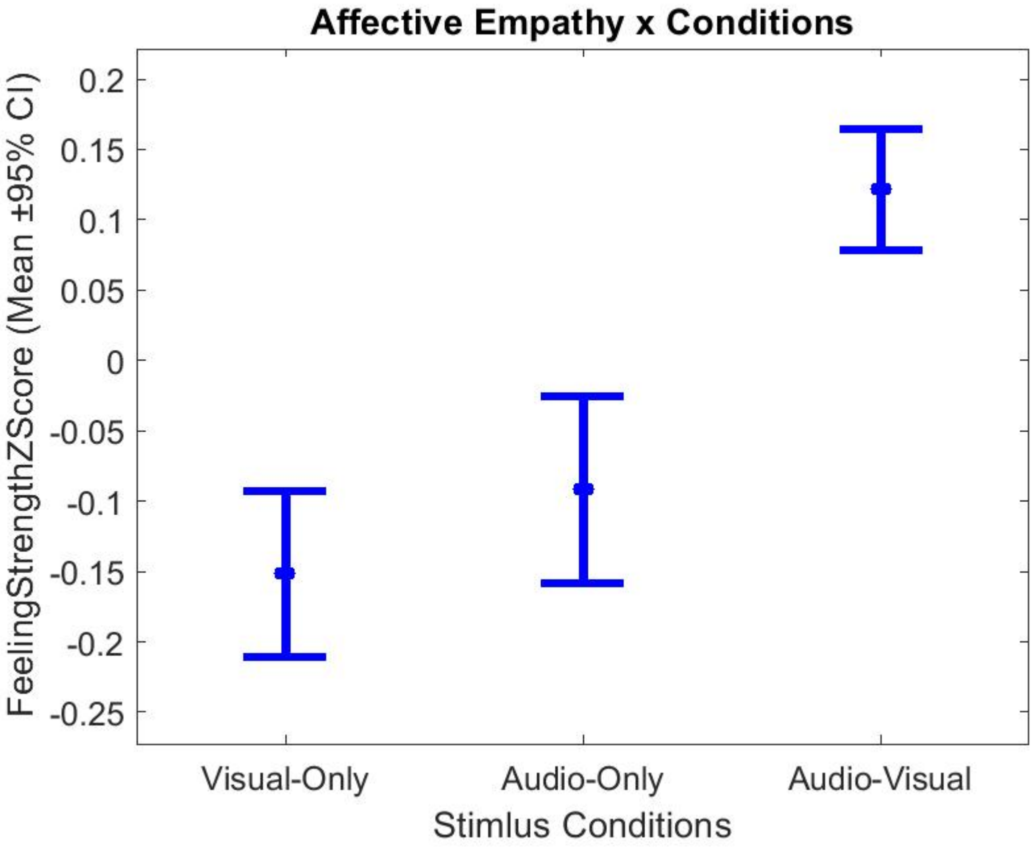

Figure 6.5: A comparison of the Feeling Strength Z-Score for the Visual-Only, Audio-Only and Audio-Visual conditions. The error bars represent the 95% confidence interval around the mean.

6.4.2 Effects of Tempo

I also tested if there were differences in participants' affective empathy attributable to the tempo of the auditory heartbeat. Tempo was nested inside of modality, so my GLMM also included the main effect of modality and its interaction (i.e. Modality x Tempo). I found a significant main effect of Tempo [F(1,26) = 13.24, p = 0.001], and a significant interaction of tempo with modality [F(1,26) = 12.28, p = 0.001], but the main effect of Modality was not significant. When I performed multiple comparison tests using a Bonferroni correction, I found that Fast heartbeats produced significantly higher Feeling Strength Z-Score than the Slow heartbeats ($p < 0.001$), but there was no significant difference between the two tempos in the Audio-Visual condition. This means that in the absence of visual stimuli, a faster heartbeat tempo was associated with higher affective empathy than a Slow heartbeat, but when there were eyes present, participants reported similar levels of affective empathy in both tempos. Figure 6.6 displays the means and 95% confidence intervals for these conditions and their interaction with tempo graphically.

6.4.3 Effects of Congruency

I also tested if there were differences in participants' affective empathy attributable to the congruency of the heartbeat and the eyes. Congruency was nested inside of tempo, so my GLMM also included the main effect of tempo and its interaction (i.e. Tempo x Modality). I found a significant main effect of Congruency [F(1,26) = 10.49, p = 0.003], but the main effect of tempo and the interaction of tempo and congruency were not significant. For the Audio-Visual trials, affective congruency between the tempo of the heartbeat and the eyes was associated with higher levels of affective empathy. This means that participants leveraged the affective content of both the visual and auditory stimuli when making their judgements, and that they reported higher levels of "feeling what the other was feeling" when the affective content was Congruent. Figure 6.7 displays the means and 95% confidence intervals for these conditions graphically.

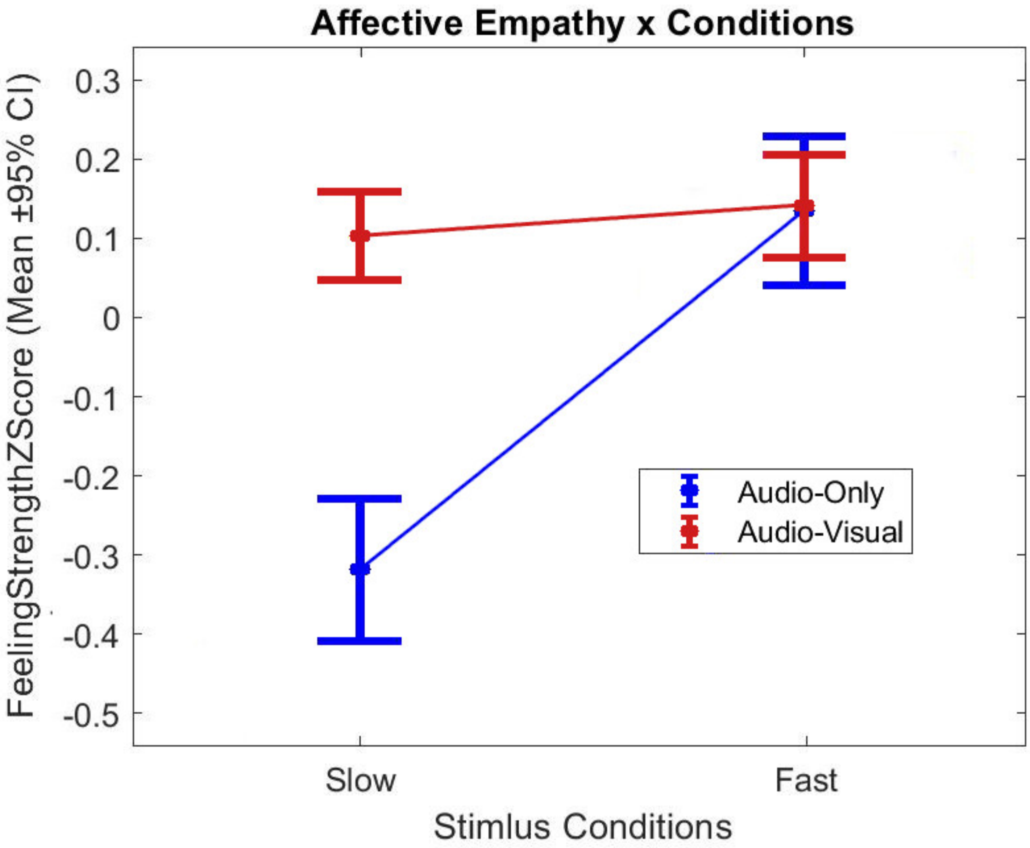

Figure 6.6: A comparison of the Feeling Strength Z-Score for Slow and Fast heartbeat tempos in Audio-Only and Audio-Visual modalities. The error bars represent the 95% confidence interval around the mean.

6.5 Relation to Traits

To understand if there were differences in the behavioral results that correlated with participant's dispositional traits, I applied Pearson correlation between the two state variables and the demographic variables listed in Section 5.6. Because this analysis was specifically concerned with differences in responses between each participant, the standardized z-score for the feeling strength was not used. Analysis was restricted to statistically significant correlations with moderate strength (i.e. $r > 0.4$) or better.

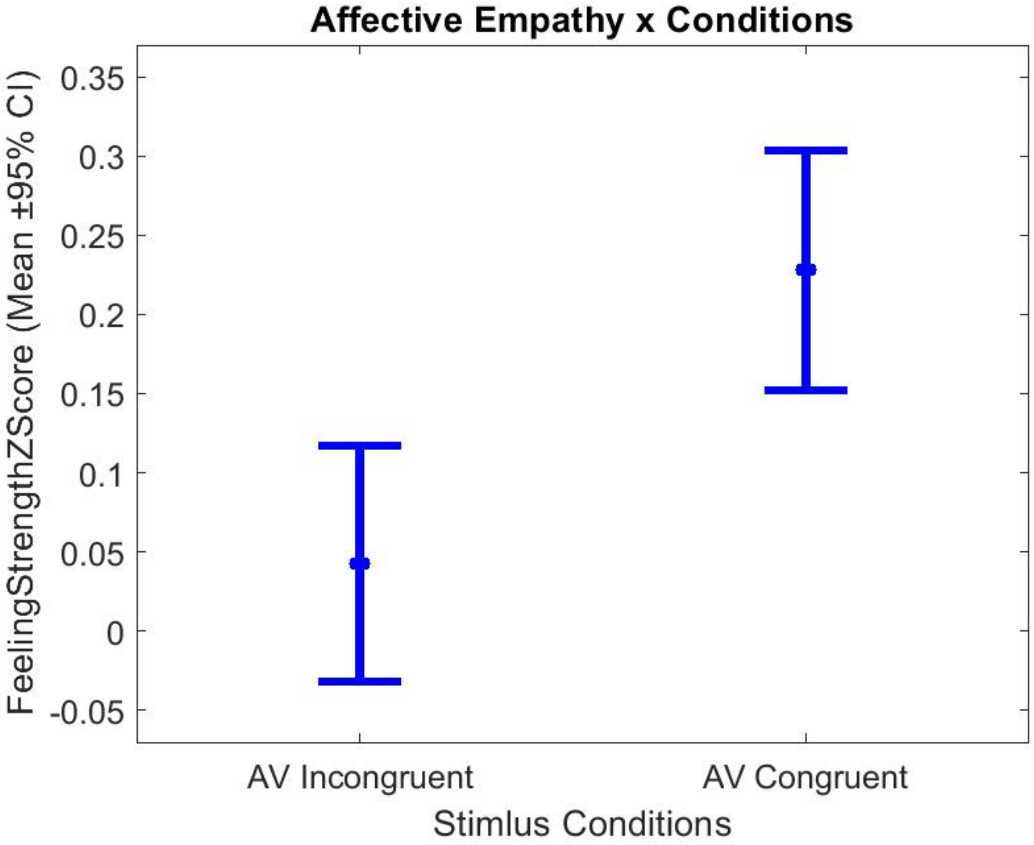

Figure 6.7: A comparison of the Feeling Strength Z-Score for Slow and Fast heartbeat tempos in Audio-Only and Audio-Visual modalities. The error bars represent the 95% confidence interval around the mean.

6.5.1 Correlations with Affective Empathy

Figure 6.8 displays the correlation between the Emotion Contagion Score and the mean of the participant's Feeling Strength scores (i.e. affective empathy) across all conditions. There was moderate positive correlation ($r(20) = 0.416$, $p = 0.031$). Emotional Contagion is a phenomenon wherein observing another person's emotional state spontaneously triggers a similar emotional state in the observer. This result means that people who had higher trait emotional contagion tended to report higher levels of ”Feeling what the other was feeling”. Because emotional contagion is contributes to the affective component of empathy [188], this result supports the validity of my question as measure of affective empathy.

Figure 6.9 displays the correlation between the IRI Fantasy scale and the mean of the

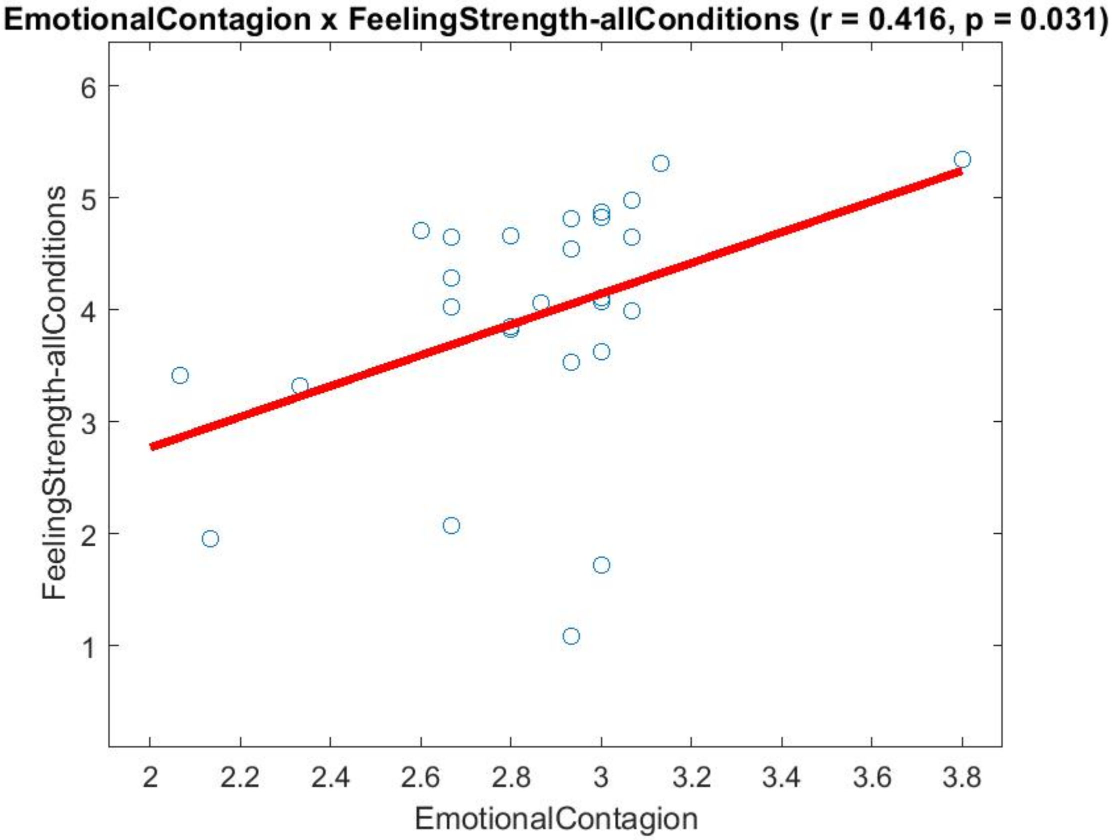

Figure 6.8: A Pearson correlation comparing the participant's mean reported Feeling Strength across all conditions versus their trait emotional contagion as determined by the Emotional Contagion Scale [224].

participant's Feeling Strength scores (i.e. affective empathy) across all conditions. There was moderate positive correlation ($r(20) = 0.409$, $p = 0.034$). The IRI fantasy scale tracks the ability of an observer to imaginatively put themselves into fictional situations and empathize with fictional characters. The observed correlation with the experimental variable of Feeling Strength means that people who have higher ability to empathize with fictional people tended to report higher levels of "Feeling what they were feeling." Given that the experiment asked the participant to determine the feelings of simulated person, it makes sense that people who have a greater ability to empathize with imagined and fictional people would report higher levels of affective empathy with the virtual/fictional people in the experiment.

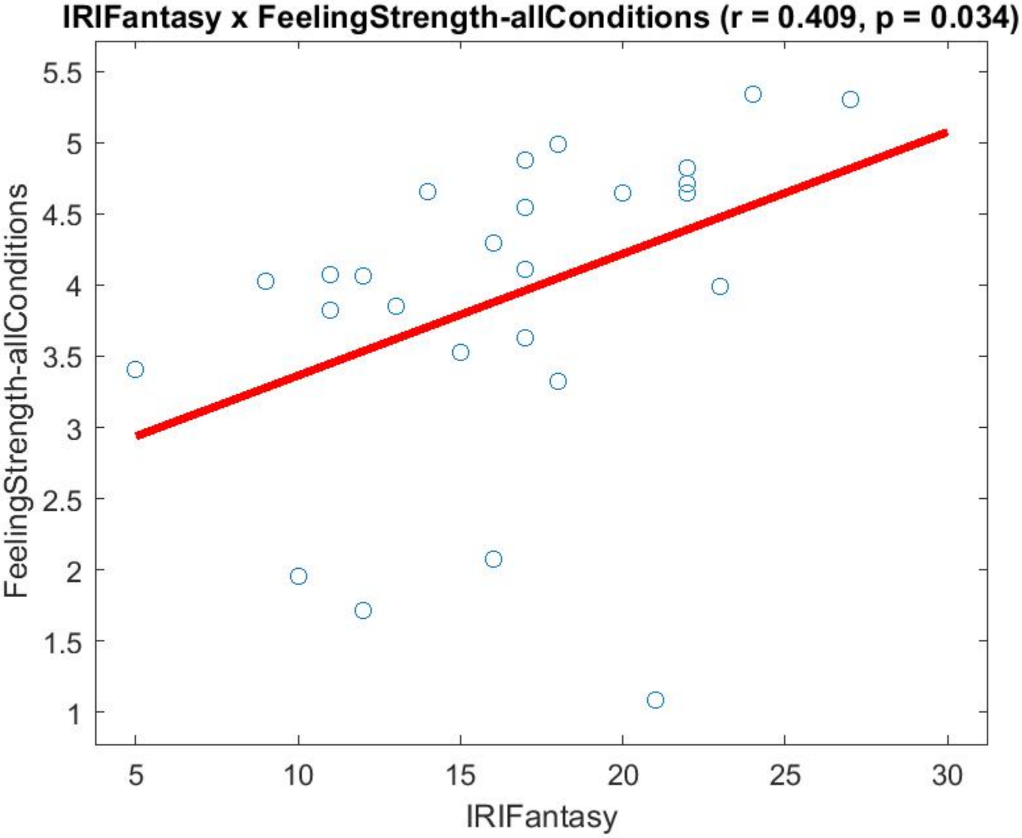

Figure 6.9: A Pearson correlation comparing the participant's mean reported Feeling Strength across all conditions versus their trait Fantasy as determined by the Interpersonal Reactivity Index [131].

6.5.2 Correlations with Cognitive Empathy

Figure 6.10 displays the correlation between each participant's baseline RMET score and their likelihood of their RMET selections changing in the experiment. There was moderate negative correlation ($r(20) = -0.608, p = 0.004$). Their baseline RMET score is an indication of their social intelligence insofar as there are "right" and "wrong" labels to each set of eyes. The observed negative correlation means that people who had lower scores in their RMET baseline were more likely to change their RMET selection in the experiment than people who scored higher in the baseline RMET. This result may mean that people who had lower scores in the RMET were more susceptible to changes in cognitive empathy when the audio-stimulus was added. A future study could determine if people with lower baseline RMET would become "more correct" in the Audio-Visual Congruent condition. If so, this would support the utility of auditory heartbeats as a technology for augmentative and alternative communication (AAC).

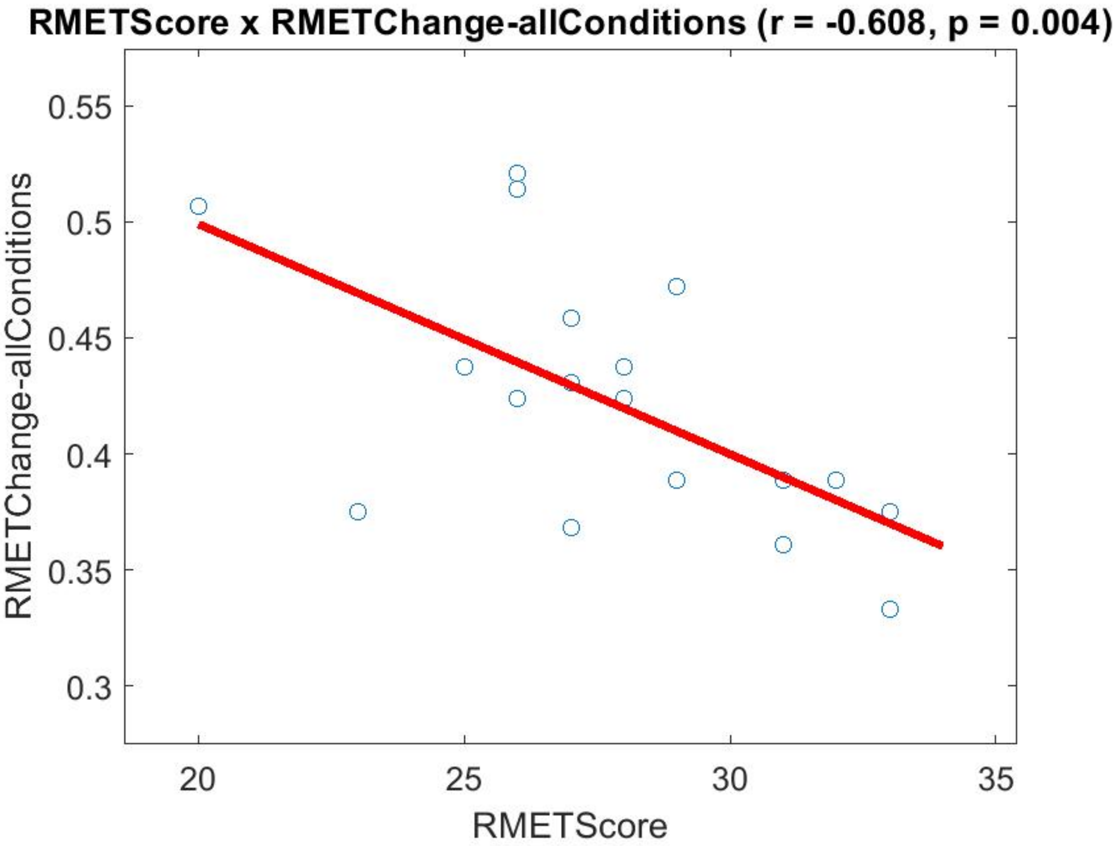

Figure 6.10: A Pearson correlation comparing the participant's score in the pre-trial baseline RMET versus their subsequent probability of changing their score on the RMET in the experiment.

CHAPTER 7

CHANGES IN HEARTRATE

7.1 Introduction

Chapter 6 demonstrated that hearing the heartbeat of an imagined person affects cognitive and affective components of empathic state. My experiment design allowed a nuanced analysis of these effects according to modality, tempo and congruency between audio-visual modalities.

Previous research had demonstrated that music, tempo and empathic state created physiological changes in listeners (Sec. 3.4). My experimental design used a simple rhythmic auditory stimulus attributed to the affective state of an imagined person, and asked participants questions designed to measure the empathic response. I hypothesized that the heartrate of the participants would be affected by this listening task (H2). Specifically, exposure to auditory heartbeats would decrease listener's heartrate (H2.1), and there would be differences in heartrate due to heartbeat tempo (H2.2) and affective empathy (H2.3).

Based upon my piloting, I hypothesized that significant changes due to stimuli and empathic state would appear with 20s of stimulus presentation. However, the present experiment was four times longer than my pilots and included multimodal (as opposed to Audio-Only) stimuli. Therefore, for the purposes of this thesis, I took an exploratory approach to heartrate data analysis. I tested specific hypotheses regarding the effects of modality (H2.1), tempo (H2.2) and affective empathy (H2.3), but also report effects independent variables, their nestings and interactions with empathy that reached my threshold for statistical significance (i.e. $\alpha = 0.05$).

7.2 Pre-Processing

To calculate the heartrate of each trial, I analyzed the ECG signal from 10s before the start of the trial to 30s after the trial start. The 10 seconds before the start of the trial was used as trial baseline measurement, and the 30 seconds after the start of the trial was used for analysis. It included the 20 seconds of stimulus presentation and 10 seconds of rest/baseline prior to the next trial.

I used a MATLAB implementation[1] of the Pan-Tompkin QRS detection algorithm [233] to identify the QRS complexes and extract the temporal location of the R peaks. I used the location of the R-peaks to determine the listener's heartrate. When using the Pan-Tomkin function, I noticed that the algorithm would occasionally miss R-locations at the start and end of the analysis window. To remedy this issue, I added a 1-second buffer to the start and end of the window that I later discarded.

7.2.1 Data Cleaning

Some of the trials contained artifacts and bad data due to a poor connection of the ECG lead and the skin. Therefore, I applied a data cleaning algorithm to mark trials that would be excluded from analysis. I first marked any trials where there was no heartbeat detected for greater than 1.8 seconds at any point in the middle of the trial. I then marked any trials where the detected heartrate across the trial was less than 40BPM or greater than 140BPM, which I viewed as unreasonably fast or slow. Finally, I marked any trials without any detected R-peaks in the first or last two seconds of the analysis window. I inspected all of the trials that had been marked to verify that that no good trials were included. I then inspected the remaining data to verify that only complete trials with correctly detected R peaks remained.

Due to an issue with the amplifier battery, I was unable to record ECG for the last

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[1] Available Online: https://www.mathworks.com/matlabcentral/fileexchange/45840-complete-pan-tompkins-implementation-ecg-qrs-detector, Date Accessed: October 23, 2019.

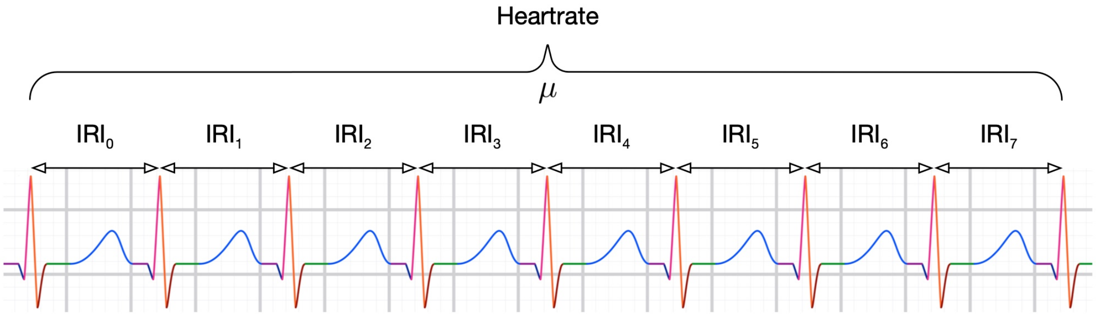

Figure 7.1: The heartrate was calculated from the mean Inter-R Interval (IRI) of the ECG waveform over fixed windows of time.

$\approx$ 30% of trials for participants 1 through 4. These trials were also excluded from my analysis.

7.2.2 Calculation of Heartrate Change

After cleaning the data, I calculated the instantaneous heartrate in 10-second windows spaced at 5-second intervals. For each window, I took the reciprocal of the mean R-R interval for all R-peaks in the window (beats/second), and then multiplied this quantity by 60 to arrive at the beats per minute (BPM). I subtracted the trial baseline BPM (i.e. -10s to 0s) from the all windows to determine the change in heartrate from trial baseline at each window. Figure 7.1 illustrates how the heartrate was determined in each window.

7.2.3 Selection of Time-Window

My previous piloting had revealed that there were significant differences in heartrate due to high and low empathy in the 0-10s and 5-15s windows, and differences due to tempo in the 15-25s window. For the purposes of data exploration, I analyzed all windows, but I present my results from the 5-15s window. My use of relatively short-windows time-locked to an acoustic stimulus onset is similar to studies on the cardiac orienting response [215, 216], which report significant decreases in heartrate due to novel audio-features shortly after stimulus onset.

7.2.4 Empathy Differences within Conditions

I hypothesized that differences in affective empathy could be measured in the participant's heartrate. For example, high affective empathy might be associated with a higher or lower heartrate relative to low affective empathy. To perform this analysis, I formed high and low affective empathy groups using the Feeling Strength Z-Score variable. The bottom 1/3 of trials (i.e. Feeling Strength Z-Score $<$ -0.431) were grouped as "low affective empathy" and the top 1/3 of trials (i.e. Feeling Strength Z-Score $>$ 0.431) were grouped as "high affective empathy." I then compared the heartrate between low and high affective empathy groups.

7.3 Heartrate Effects: Full Experiment

7.3.1 Effects of Modality

Based upon previous research (e.g. Secs 3.4.2 & 3.4.3), I hypothesized that hearing the sound of another person's heartbeat would decrease the heartrate of the listener (H2.1). This means that the auditory perception of another person's beating heart, created a physiological calming response. To test for this effect, I compared the change in heartrate from baseline for the Visual-Only, Audio-Only and Audio-Visual conditions of my study. If there was not an effect of the auditory heartbeat on the heartrate of the listener, then there would be no statistically significant difference in the change in heartrate from baseline between the Visual-Only and either of the two audio conditions.

However, I found a statistically significant decrease in heartrate from trial baseline due to the presence and introduction of an auditory heartbeat [F(2,3233) = 7.92, $p < 0.001$], rejecting the null hypothesis from H2.1. I also found no change in heartrate from trial baseline in the Visual-Only group, while both the Audio-Only and the Audio-Visual groups had a significant decrease in heartrate relative to trial baseline. This may suggest that the effect of hearing the auditory heartbeat was to create a calming/relaxation response

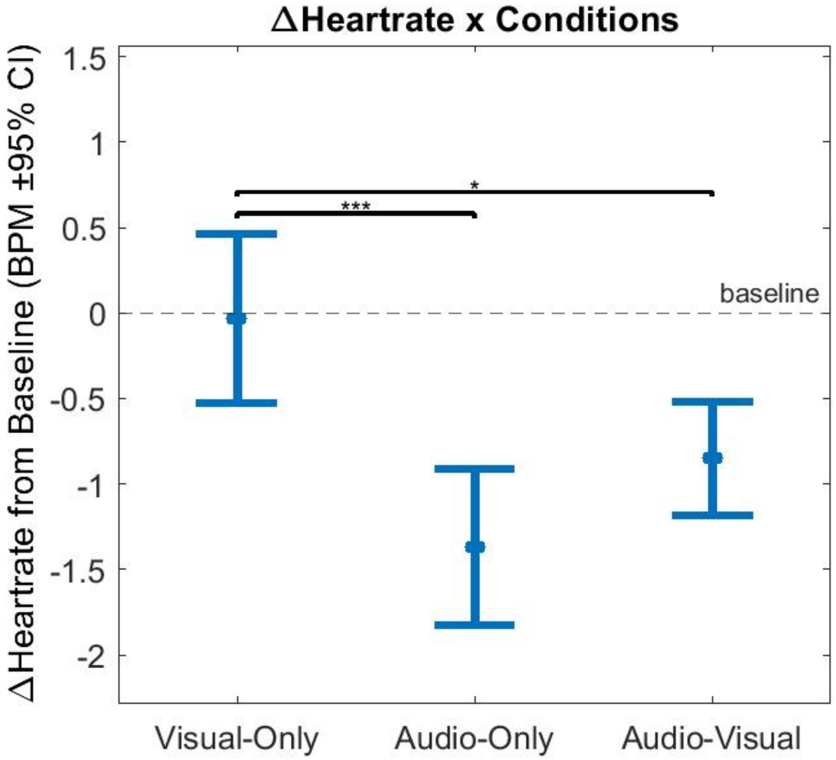

Figure 7.2: A comparison of the change in heartrate in the Visual-Only, Audio-Only and Audio-Visual conditions. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

in the listener's autonomic nervous system. Multiple comparison tests revealed that the change in heartrate from baseline was significantly lower than the Visual-Only condition in the Audio-Only condition ($p < 0.001$) and the Audio-Visual condition ($p < 0.05$). Further, there was no significant difference between the Audio-Only and the Audio-Visual conditions. Because a decrease in heartrate was found in the Audio-Visual condition but not in the Visual-Only condition, the decrease in heartrate was likely driven by the presence of the auditory heartbeat rather than the visual stimulus. Figure 7.2 displays the means and confidence intervals of these three groups graphically.

Affective Empathy

I also compared the heartrate change from trial baseline between the low and high affective empathy groups in these three modalities. If there was a difference between high and low empathy groups, it would mean that differences in empathic state were accompanied by differences in listeners' change in heartrate in the auditory heartbeat conditions (H2.3).

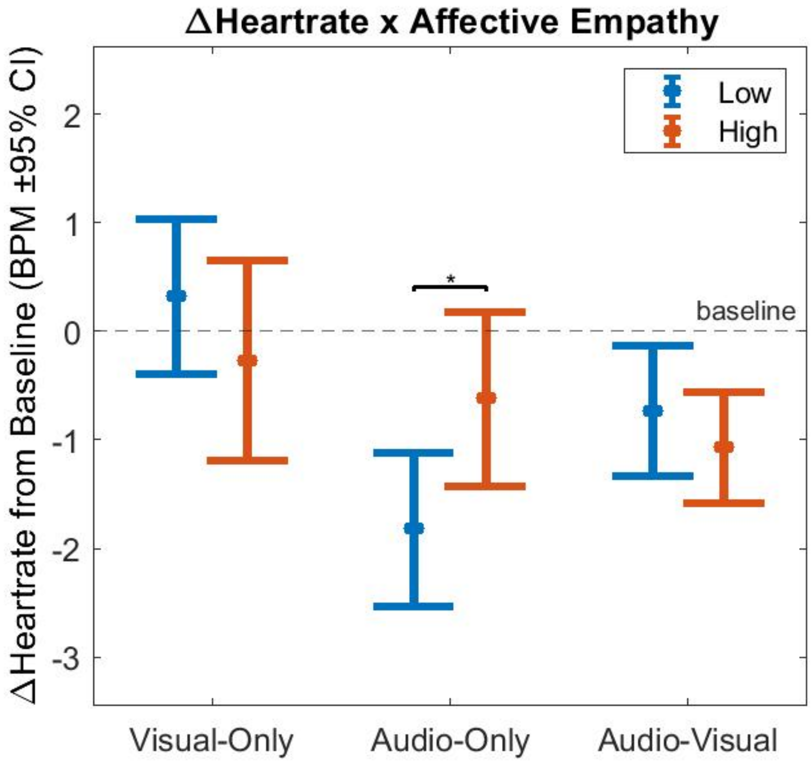

Figure 7.3: A comparison of high and low affective empathy groups in the Visual-Only, Audio-Only and Audio-Visual conditions. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

I found a significant difference between the high and low affective empathy groups in the Audio-Only condition $[t(572) = -2.2, p = 0.029]$, rejecting the null hypothesis for H2.3. This means that when participants listened to the heartbeat without a visual stimulus, different physiological states accompanied their reports of high or low affective empathy. In particular, high affective empathy trials had a relatively higher change in heartrate from trial baseline than low affective empathy trials, though still were both below baseline.

This indicates a relatively higher arousal level associated with high affective empathy and lower arousal level associated low affective empathy. Because this effect was specific to the Audio-Only condition, it may indicate that when participants listened to the heartbeat without a visual stimulus, their self-reports of high or low affective empathy aligned with their own physiological arousal-level. Further, because trials with lower affective empathy were associated with greater decreases in heartrate from trial baseline, this result could also mean that these participants were more physiologically affected by the acoustic intervention. Participants may have used other factors in their report of high or low affective empathy in trials when the visual stimulus was present. Figure 7.3 displays the means and confidence intervals for these comparisons graphically.

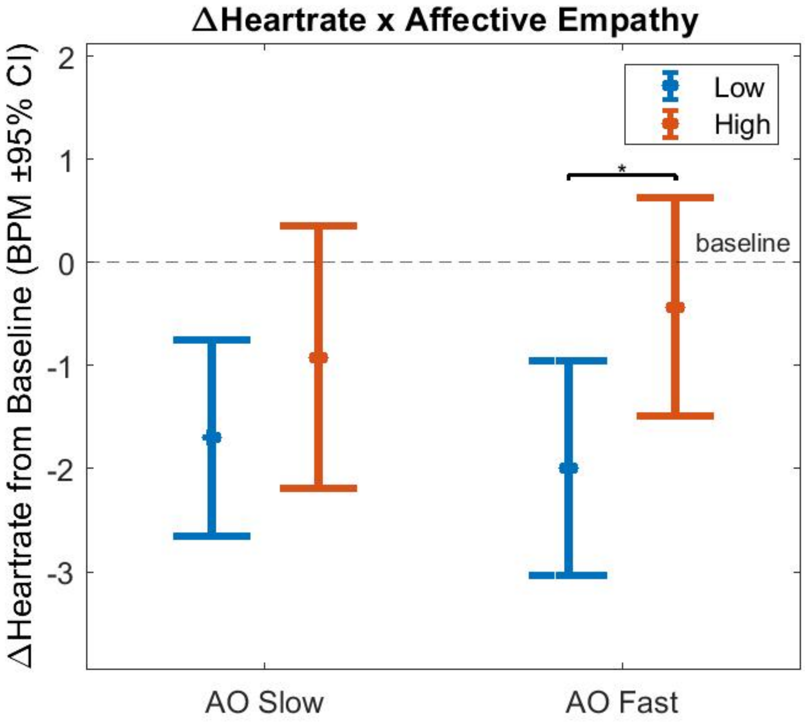

Figure 7.4: A comparison of high and low affective empathy groups in the Audio-Only Slow and Audio-Only Fast conditions. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

Because I found a statistically significant difference in heartrate change from trial baseline between high and low empathy groups in the Audio-Only condition, I was curious if there was a difference between the Slow or Fast auditory heartbeat conditions. A difference between these two groups would indicate differences due to tempo.

I found a statistically significant difference in the heartrate change from trial baseline between high and low affective empathy groups in the Audio-Only Fast trials $t(287) = -2.05, p = 0.041$, but not in the Audio-Only Slow condition. This means that the Audio-Only Fast condition contributed more to the affective empathy difference found in Figure 7.3. This result may be related to the findings of Section 6.4.3, which found that participants' reported higher levels of affective empathy in the Fast Audio-Only condition than Slow Audio-Only condition. This result further supports H2.3 because the higher levels of affective empathy found in the Audio-Only Fast condition were accompanied by a greater difference in heartrate between high and low affective empathy groups. Figure 7.4 displays the means and confidence intervals associated with this comparison.

7.3.2 Effects of Congruency

In Section 6.4.3, Audio-Visual congruency was associated with higher affective empathy than Audio-Visual incongruency. By H2.3, I reasoned that Audio-Visual congruency would also manifest in relatively higher heartrates than Audio-Visual incongruency. To test for this effect, I compared the change in heartrate for the Congruent and Incongruent Audio-Visual conditions. If there was not an effect of the congruency of the Audio-Visual stimulus, then there would be no difference in participants' heartrates between these two conditions.

However, I found a statistically significant difference in heartrate change from trial baseline due to the congruency of the Audio-Visual stimulus $[F(1{,}1073) = 6.76, p = 0.009]$. Listeners heartrate was relatively higher when the affective content of the Audio-Visual stimuli was Congruent relative to when it was Incongruent, indicating a relatively greater arousal-level in this condition. Figure 7.8 displays the means and confidence intervals of these two groups graphically.

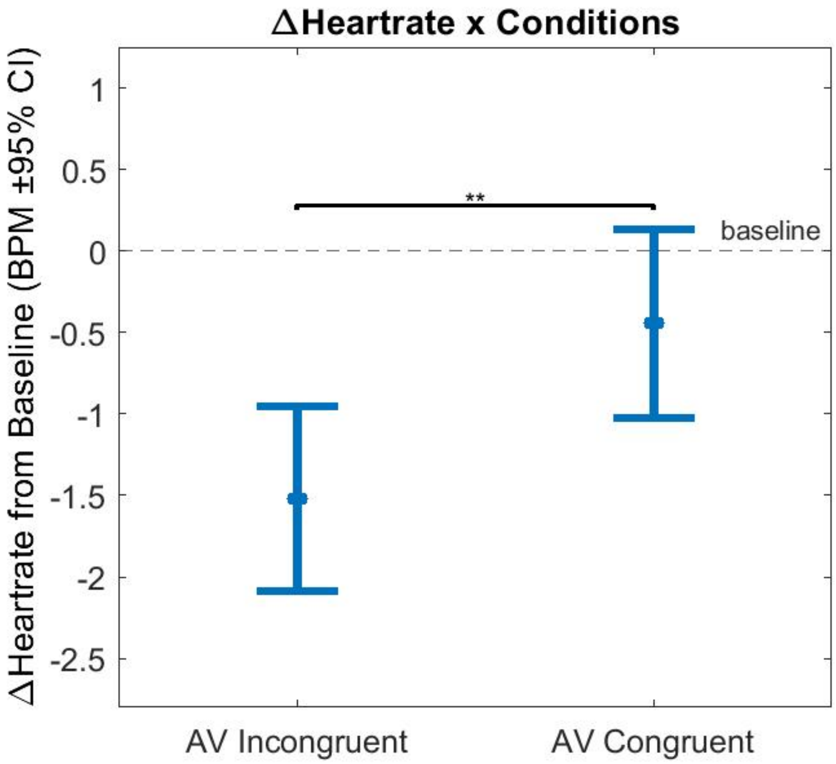

Figure 7.5: A comparison of change in heartrate for the Audio-Visual Incongruent and Audio-Visual Congruent conditions. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

7.3.3 Effects of Tempo

I hypothesized that the tempo of the auditory heartbeat would affect the participant's heartrate. This would mean that hearing a slow heartbeat or a fast heartbeat produced differences in the listener's physiology. I also hypothesized that hearing a fast heartbeat would create a higher heartrate than a slow heartbeat, indicating listener's physiology followed the arousal-level in the auditory stimulus. To test for this effect, I compared the change in heartrate for the Audio-Only Slow, Audio-Only Fast and the Audio-Visual Slow and Audio-Visual Fast conditions. If there was not an effect of heartbeat tempo, then there would be no difference in heartrate between the Fast or Slow conditions.

I found no statistically significant difference between the Audio-Only Slow and Audio-Only Fast conditions $[t(820) = -1, p = 0.32]$, and no statistically significant difference between the Audio-Visual Slow and Audio-Visual Fast conditions [$t(1616) = 1.75, p = 0.081$]. These results do not reject the null hypothesis for H2.2. The tempo of the auditory heartbeat did not have a significant effect on the heartrate of the listener over all of the recorded data averaged across participants. However, Section 7.4 describes a subsequent analysis of the first 36 trials (25%), which did find this difference.

7.4 Heartrate Effects: First 36 Trials

My pilot testing had found significant differences in heartrate due to the tempo of the auditory heartbeat as well as affective empathy. I was curious why I did not find similar differences in my analysis of heartbeat tempo in Section 7.3.3. However, the experiment I conducted was over four times as long as my pilots, so I reasoned that the length of the study may have fatigued participants and limited the physiological effects.

To limit the effects of fatigue on the analysis, I decided to perform a new analysis on the first 36 trials in the experiment. This corresponded to the first 18 minutes of the experiment and first 25% of trials. Because my experiment included 27 participants, the first 36 trials for each participant created a total of 972 trials for analysis.

For this analysis, I also limited analysis to the first 0-10s of each trial. I found similar effects on the time window of 5-15 seconds, but reasoned that focusing on the first 10 seconds of the trial would be advantageous to future iterations of the study. If similar results could be found with shorter trials, future studies could be shorter, allow more time for rest/baseline between trials, or allow for more trials in the same amount of time.

As in Section 7.3, I looked for differences in heartrate between experimental conditions and differences in heartrate within each condition that were attributable to differences in empathic state.

7.4.1 Effects of Modality

In my analysis of the full 144 trials, I found a significant difference in heartrate change from trial baseline between the high and low affective empathy groups in the Audio-Only condition. I was curious if such an effect was present in the first 36 trials as well. I therefore compared the heartrate between the high and low affective empathy groups across the three modalities. If there was no difference in heartrate between the groups, then participant's self-reported high or low affective empathy did not correspond to a difference in physiology for that condition.

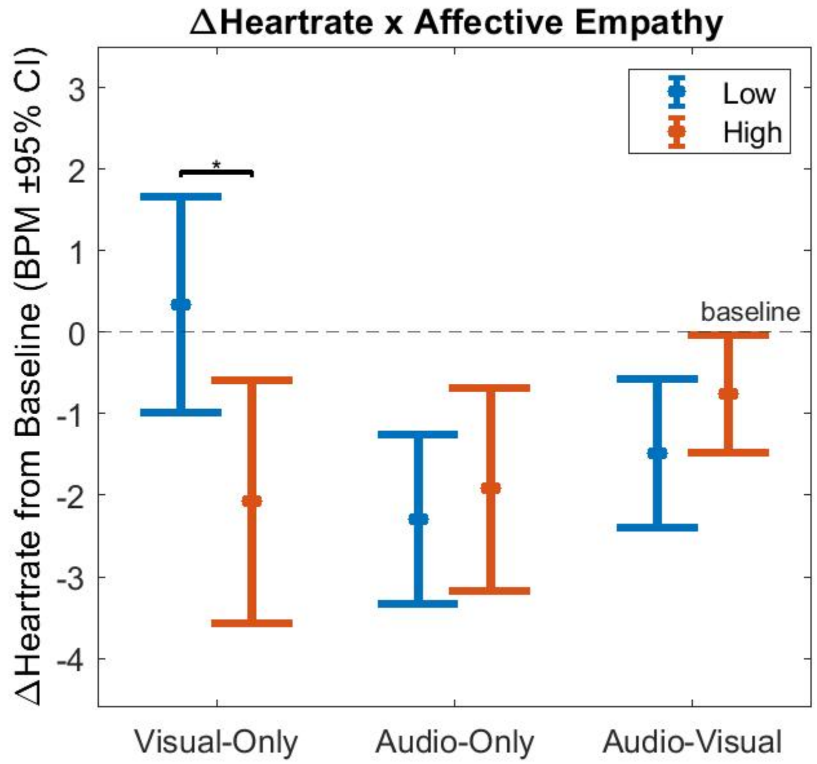

Figure 7.6: A comparison of low and high empathy groups in the Visual-Only, Audio-Only and Audio-Visual trials. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

In the first 36 trials, I found a significant difference in heartrate change from trial baseline between high and low affective empathy groups in the Visual-Only condition $[t(140) = 2.29, p = 0.024]$ and no significant differences in either the Audio-Only or the

Audio-Visual conditions. This finding was in contrast to my analysis of the three groups across all 144 trials, where I found a significant difference in the Audio-Only condition, but not the Visual-Only condition. Furthermore, in the Visual-Only condition, high affective empathy was associated with a relatively lower heartrate, whereas in the Audio-Only condition, it was associated with a relatively higher heartrate.

This difference may indicate differences in affective empathy due to modality or that participants responded in different ways to the affective empathy question for different modalities. For example, when participants started the experiment, they might have associated higher levels of affective empathy in the Visual-Only condition when they were in a state of greater physiological relaxation, while reporting higher levels of affective empathy in the Audio-Only condition when they were in a state relatively greater physiological arousal. In either case, there was a relationship between participant's self-reported affective empathy and their physiological state. Figure 7.6 displays these means and confidence intervals graphically.

7.4.2 Effects of Congruency

I previously found a significant difference in the heartrate of participants in the Congruent and Incongruent Audio-Visual conditions and wanted to determine if there were differences in heartrate associated with high or low affective empathy. I therefore compared the heartrates of the low and high affective empathy groups for the Congruent and Incongruent Audio-Visual conditions. If there were no differences between these two groups, it would mean that participants' self-reported ratings of affective empathy did not correspond with differences in physiological state.

However, I found a significant difference in change in heartrate from trial baseline between the high and low affective empathy groups in the Congruent Audio-Visual condition $[t(96) = -3.2, p = 0.002]$. This means that when the tempo of the heartbeat matched the arousal-level in the eyes, participant's reports of high or low affective empathy corre-

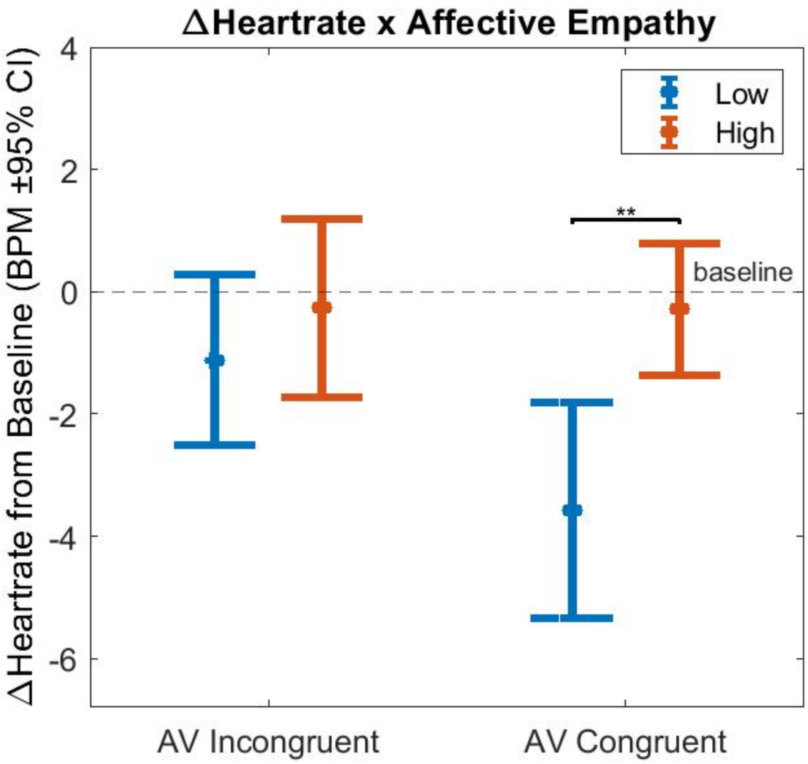

Figure 7.7: A comparison of high and low affective empathy groups in the Audio-Visual Incongruent and Audio-Visual Congruent trials. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

sponded to differences in heartrate. In particular, high affective empathy was associated with a relatively higher heartrate than low affective empathy. This indicates that when participants observed Congruent Audio-Visual stimuli, high affective empathy was associated with a relatively higher degree of physiological arousal. Figure 7.7 displays these means and confidence intervals graphically.

Congruency & Speed

Having found a significant difference between the low and high empathy groups in the AV Congruent condition, I was curious if there was a difference due to the tempo of the auditory heartbeat. I tested this by comparing the heartrates between the Congruent Fast and Congruent Slow conditions. If there was no difference in between these two conditions, then there would be no significant difference in the change in heartrate from trial baseline between the two empathy groups.

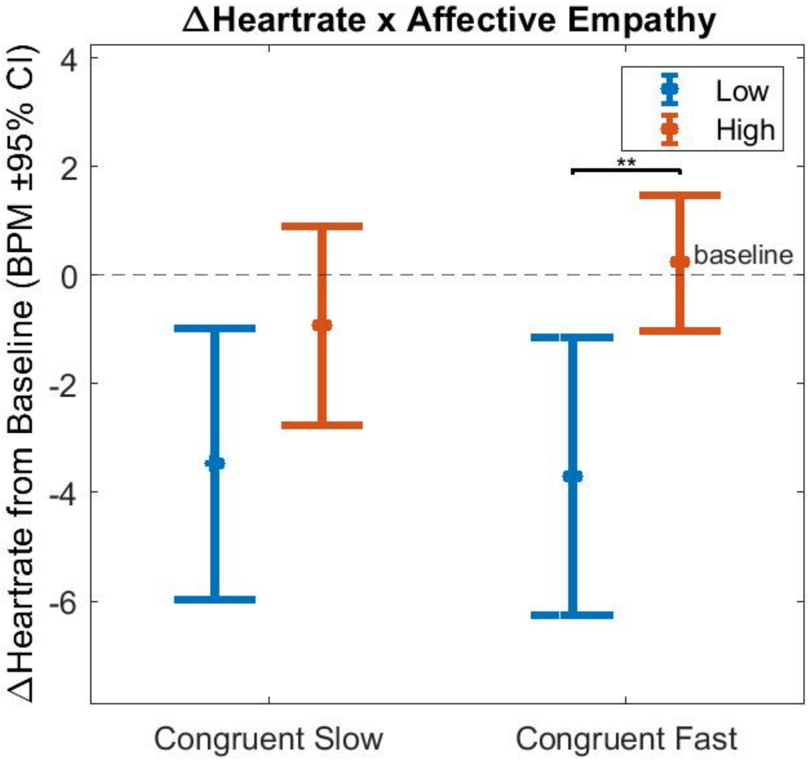

Figure 7.8: A comparison of high and low empathy groups in the AV Congruent Slow and AV Congruent Fast conditions. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

However, I found a significant difference in heartrate change from trial baseline for the Fast group $[t(49) = -2.96, p = 0.005]$, but not the Slow group. Furthermore, listeners had relatively higher heartrates when they reported high affective empathy in the Congruent Fast condition. This means that the difference in heartrate between the high and low empathy groups in the Audio-Visual Congruent condition was mostly due to the high empathy response to Fast auditory heartbeats.

7.4.3 Effects of Tempo

My previous piloting had found significant differences in listeners' heartrates due to the tempo of the auditory heartbeat. I was curious if these effects were present in the first 36 trials. I tested this by comparing the heartrates in the in the Fast and Slow auditory heartbeat conditions in the Audio-Only and Audio-Visual conditions. If there was no effect, it would mean that the tempo of the auditory heartbeat did not create differences in the physiology of the listener.

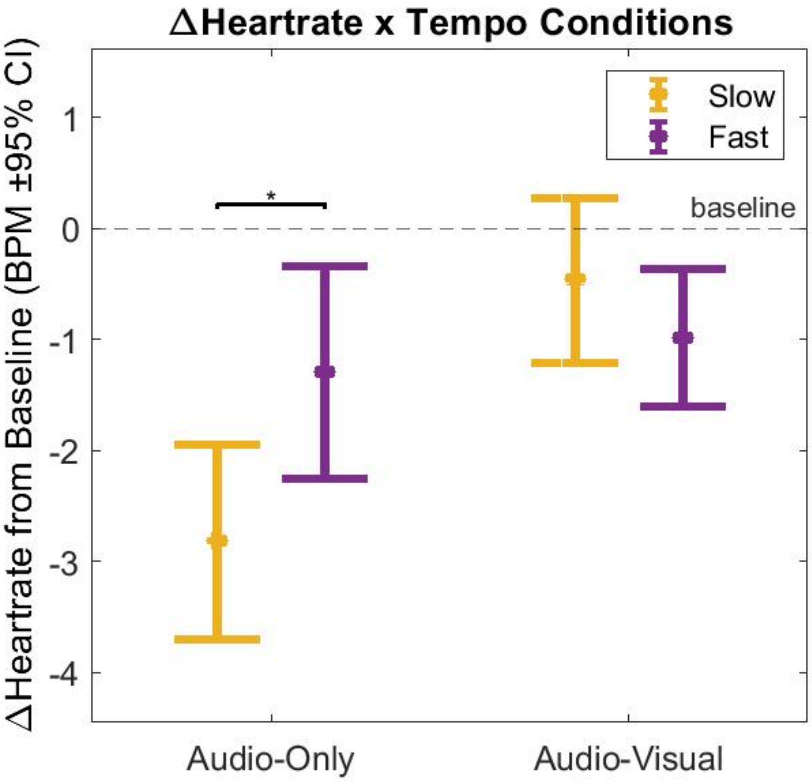

Figure 7.9: A comparison of changes in heartrate due to Slow and Fast heartbeats in the Audio-Only and Audio-Visual conditions. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

However, I found a significant difference in the change in heartrate from trial baseline between the Fast and Slow heartbeats in the Audio-Only condition $t(231) = -2.31, p = 0.022]$, rejecting the null hypothesis for H2.2 in the Audio-Only condition in the first 36 trials. This means that the participant's physiological response depended upon whether they heard Fast or Slow heartbeats. In particular, Fast auditory heartbeats were associated with a significantly higher change in heartrate from baseline than the Slow auditory heartbeats, in line with the expectations of physiological entrainment [31]. Figure 7.9 displays these means and confidence intervals graphically.

The lack of a difference in heartrate due to Fast or Slow in the Audio-Visual condition may indicate a special role for listening attention in changing heartrate. In essence, when participants saw and heard the person, part of their attention was directed to the visual content, which perhaps distracted their listening attention. Alternatively, answering the question of “What is this person feeling” in a condition without visual stimuli might have prompted some participants to attempt to mirror the physiological state internally as a way of “imagining” what the person was experiencing.

7.4.4 Cognitive Empathy

I also explored whether changes in cognitive empathy were associated with differences in heartrate. For this analysis, I formed two groups according to whether participants’ answer to the cognitive empathy question changed or did not change from pre-experiment baseline. I then compared the change in heartrate from pre-trial baseline between these two groups. If there was a difference in heartrate between the two groups, it would mean that a change in the participant’s perspective on the affective state of the imagined person was associated with a difference in physiological state. If there was not a significant difference between the heartrates of the two groups, it would mean that changes in cognitive empathy were not associated with changes in physiology.

Across all conditions, I found a significant difference in heartrate change from trial baseline between the two cognitive empathy groups $[t(636) = 2.77, p = 0.006]$. In particular, trials where participants’ changed their affective perspective were associated with a relatively lower heartrate than trials without a change in affective perspective. Figure 7.10 displays the means and confidence intervals of this comparison graphically.

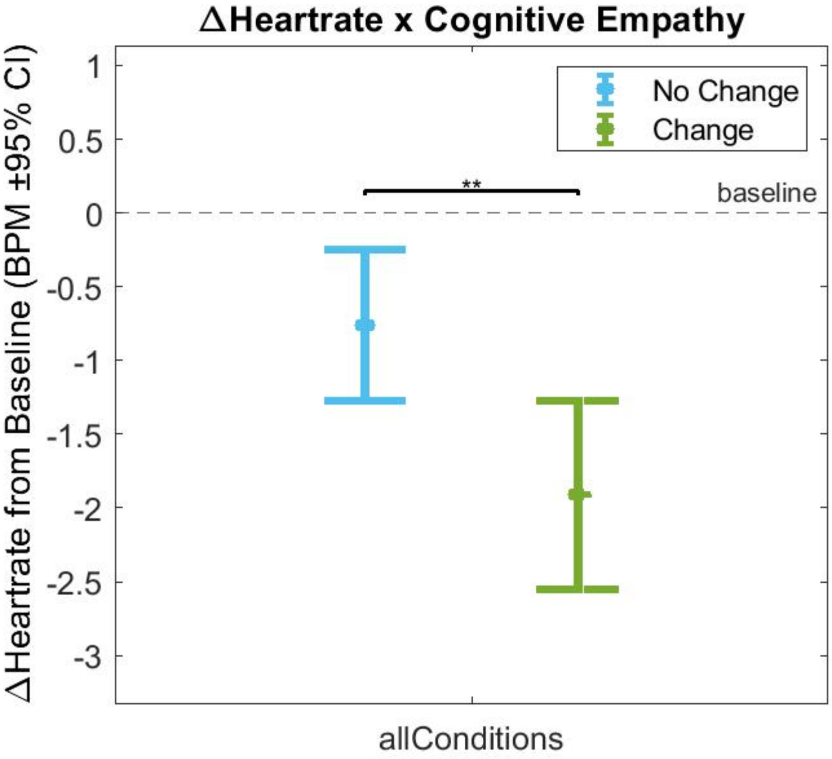

Figure 7.10: A comparison of changes heartrate for trials with Change or No-Change in cognitive empathy. The Y-Axis displays the change in heartrate from trial baseline including error bars representing the 95% Confidence Interval.

This finding could be related to H2.3 and the findings of Section 6.4.3. Namely changes in cognitive empathy were associated with relatively lower ratings of affective empathy, which have been associated with a lower heartrate. Alternatively, the significant decrease in heartrate associated with a change in cognitive empathy could be related to attention. People who were distracted from the task might be more likely to answer differently than their pre-trial RMET, and their lack of attention might also appear in a decrease in heartrate. However, this second explanation is not likely because the effect was not found across all trials, where fatigue and distraction are presumed to have played a large role.

7.5 Conclusions

My results suggest that the effect of empathic listening to an auditory heartbeat was to decrease the heartrate of listeners. The effect was most pronounced when there was no visual stimuli present (i.e. the Audio-Only condition). Within the auditory stimuli, Fast heartbeats, Congruent Audio-Visual stimuli, and high affective empathy were associated with relatively faster heartrates than slower heartbeats, Incongruent Audio-Visual stimuli and low affective empathy. However, none of the heartrates in these conditions were statistically higher than trial baseline measurement.

There are two ways of interpreting these secondary findings, namely i) there was no significant difference in heartrate change from trial baseline for any auditory conditions except those that created significantly lower heartrates than trial baseline or ii) there was an overall “main” effect of the auditory stimuli to decrease heartrate, but within this overall decrease there were additional significant differences due to tempo, congruency and empathy relative to the mean of that condition. Based upon an analysis of the time-course of the heartrate in the auditory conditions, I take the second position. Within the first 5 seconds of stimulus exposure, there is a significant decrease in heartrate for all auditory conditions. From that point, trials with fast heartbeats, audio-visual congruency and high affective empathy distinguish themselves from trials with Slow heartbeats, audio-visual incongruency, and low affective empathy by rapidly increasing in heartrate, leading to the significant difference between the two conditions by the end of the trial. It is possible that another experiment with longer auditory heartbeat presentations (i.e. greater than 20s), would have found that these faster heartrate conditions increased to a level significantly above trial baseline.

CHAPTER 8

CHANGES IN THE HEARTBEAT EVOKED POTENTIAL (HEP)

8.1 Introduction to the Heartbeat-Evoked Potential

For the duration of the experiment, the participant was connected to a BrainVision 64-channel active EEG amplifier with auxiliary inputs that synchronized the EEG with the participant's ECG and audio. The details of that recording process can be found in Section 5.11. As opposed to fMRI, which offers superb spatial resolution, EEG offers temporal precision of the ongoing neural dynamics. This ability has contributed research into the temporal processes in the neuroscience of empathy ([153], Sec. 3.1.5). Such insights are commonly revealed by aligning multiple trials to the same time-point within each trial (epoching). The so-called Event-Related Potential (ERP) is then used to infer differences in cortical processing between different experimental conditions [234].

For the purposes of this study, I analyzed the slow cortical potential shown to be elicited in response to the interoceptive processing of one's own heartbeat, called the "Heartbeat Evoked Potential" ([158, 35], Sec. 3.1.6). In this paradigm, we measure the ERPs in relation to the R-peaks in a typical QRS ECG waveform. This creates one ERP for every heartbeat, and subsequently hundreds of ERPs in a few minutes. After aligning the ERPs according to the R-peak, the data is cleaned using typical methods including channel reduction, low-pass filtering, Independent Component Analysis, and artifact rejection. Importantly, the Cardiac Field Artifact (CFA) is carefully isolated from the EEG to isolate true cortical sources.

8.1.1 Question & Hypothesis

Because my research paradigm uses exteroceptive (Sec. 3.1.4) auditory heartbeats as a stimulus, an interesting question arises pertaining to the cardiac response of the listener (Sec. 4.1.1). Does listening empathically to the auditory heartbeat of another person change listener's own cardiac physiology? Chapter 7 showed that listener's heartrate was affected. In this chapter, I test whether their cardiac cortical processing was also affected.

Internal physiological perception is called Interoception (Sec. 3.1.3), and is usually measured through a task designed to test the perception of one's own cardiac pulse [158]. The HEP has been shown to be more positive over fronto-central electrodes in the time range of 200-400ms with greater performance and attention to ones own heartbeat [158, 235, 35]. On the other hand, perception of others' affect in photographs [36, 38] and movies [37] has been associated with a more negative HEP amplitude over fronto-central electrodes. These positive and negative deflections may be related to an underlying interoceptive attentional mechanism that is altered and specifically diminished through attention to the physiological state of others. I therefore hypothesized that listening empathically to the heartbeats of others would alter listeners' HEPs (H3), specifically by making them more negative (H3.1).

8.2 HEP Calculation

The latency of the HEP depends upon the task, but prior work has shown that it occurs between 200ms to 600ms after the R-peak in fronto-central [158, 36, 35] and parietal [34] electrodes. After normal EEG cleaning and pre-processing procedures, an important step in calculating the HEP is to remove the the cardiac field artifact (CFA). The CFA is a much stronger signal than brain activity and is also time-locked to the R-peak of the ECG waveform. Many methods have been used including direct subtraction of the ECG wave from the ERPs, and source separation algorithms including PCA and ICA [35].

For the purposes of my study, I used independent component analysis (ICA)—a robust algorithm for blind source separation that can identify multiple overlapping cortical sources and facilitate artifact identification and removal [236]. I first applied ICA to the EEG data of each individual participant, and then used EEGLAB STUDY to perform cluster-based statistics and group similar cortical components across participants [230]. The cardiac field artifact was readily identified in the component ERPs and rejected. The remaining component clusters were non-artifactual cortical sources with known dipole locations, scalp-maps and associated ERPs.

8.2.1 Data Preprocessing

Loading and Labelling Trials

The original experiment synchronized experiment markers with EEG using Lab-Streaming-Layer (Sec. 5.5). The output was an XDF file, which included the EEG, ECG, Audio-Data and Experiment markers indicating the trial number, start and stop times. These XDF files were loaded into EEGLAB [237], a MATLAB toolbox with many functions for processing, analyzing and visualizing EEG.[1]

The individual trails of the EEG were then matched with the corresponding trial in the participant response data to mark them according to conditions. For each trial, I then calculated the position of ECG R-peaks using to the Pan Tompkin algorithm [233] as described in Section 7.2. These event locations were labelled according to the corresponding experiment condition (e.g. Visual-Only, Audio-Visual).

EEG Data Cleaning

I cleaned the data using a modified version of Makoto's preprocessing pipeline.[2] The pipeline uses several common strategies for artifact rejection [238, 239], and had been

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[1] [Available Online:] https://sccn.ucsd.edu/eeglab/index.php, Date Accessed: June 6, 2019.

[2] [Available Online:] https://sccn.ucsd.edu/wiki/Makoto's_preprocessing_pipeline, Date Accessed: June 7, 2019.

used in previous work [240, 21]. The basic steps are as following:

1. Down-sample to 250Hz
2. Apply a high-pass filter at 1Hz
3. Remove line noise at 60Hz and 120Hz
4. Identify and remove bad channels
5. Clean the data using Artifact Subspace Rejection
6. Interpolate the removed channels
7. Re-reference to a common-mode average

The exact parameters behind these steps is available in Appendix E.1.

ICA, Dipole Locations and Epoching

After cleaning the data, I used independent component analysis (ICA) to separate independent sources in the EEG data [236]. The EEG signal is assumed to come from a variety of artifactual, noise and cortical sources, and ICA decomposes the signal into a mixing matrix whose component time courses are maximally independent [241]. There are several implementations of ICA, and I used the AMICA algorithm [242].

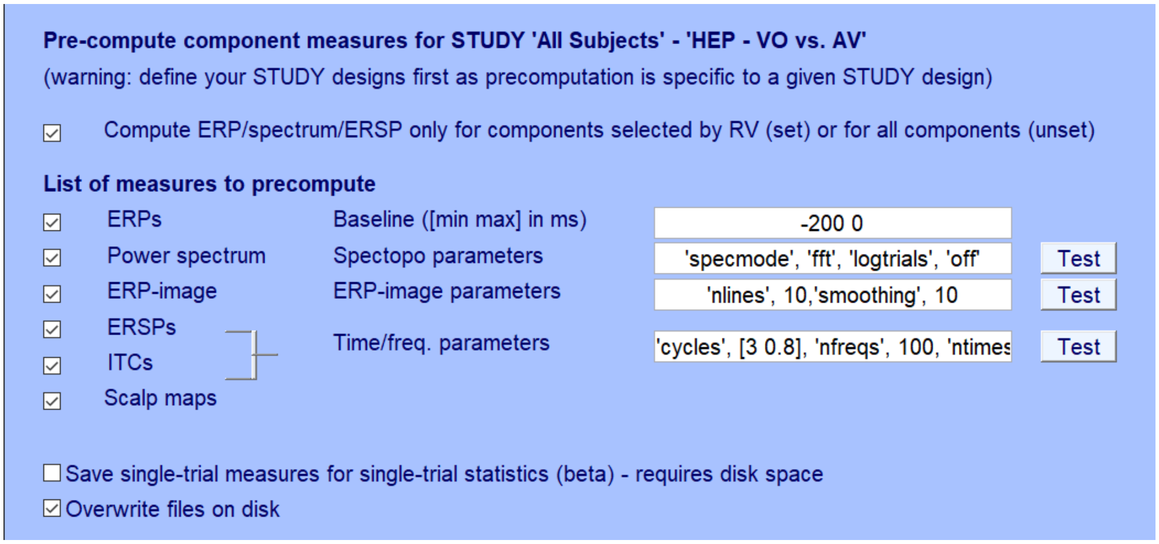
Independent Components (ICs) have associated 2-dimensional "scalp maps" that identify spatial mixing and projections over the surface the head. Researchers have found ways to associate these 2-D scalp projections with dipoles located in the cortex. To calculate these locations, I used EEGLABs DIPFIT tool [230] and the fitTwoDipoles function to search for potential sources [243].

Following these two steps, I epoched participants' individual trials from -200 to 1000ms after the R-peak in each ECG heartbeat. For each subsequent analysis, I used the time frame from -200 to 0ms as baseline. Because prior research had found that stimuli repetition could suppress the amplitude of the HEP [33], I reasoned that later trials in the experiment would have smaller differences in the HEP. Having previously limited my analysis of ECG to the first 36 trials (Sec. 7.4), I decided to also limit my EEG analysis to the same trials.

8.2.2 Grouping & Hypothesis Testing

To test my hypothesis that hearing someone's heartbeat would make the HEP more negative, I contrasted trials that were Visual-Only with trials that were Audio-Visual.

In order to group components, I began by rejecting any components that had dipoles whose residual variance (RV) was greater than 15%. Residual variance is the amount of variance in the spatial activation pattern of the scalp after projection onto a dipole model. It is a way of determining if a dipole is an appropriate fit for the data: A low RV means a better dipole fit. To identify similar components for clustering, I used STUDY's tools for calculating ERPs, power spectrum, event-related spectral perturbations (ERSPs), inter-trial coherence (ITCs) and scalp maps. Default parameters were used for all of these computations as displayed in Figure 8.1.



Pre-compute component measures for STUDY 'All Subjects' - 'HEP - VO vs. AV'
(warning: define your STUDY designs first as precomputation is specific to a given STUDY design)

☑ Compute ERP/spectrum/ERSP only for components selected by RV (set) or for all components (unset)

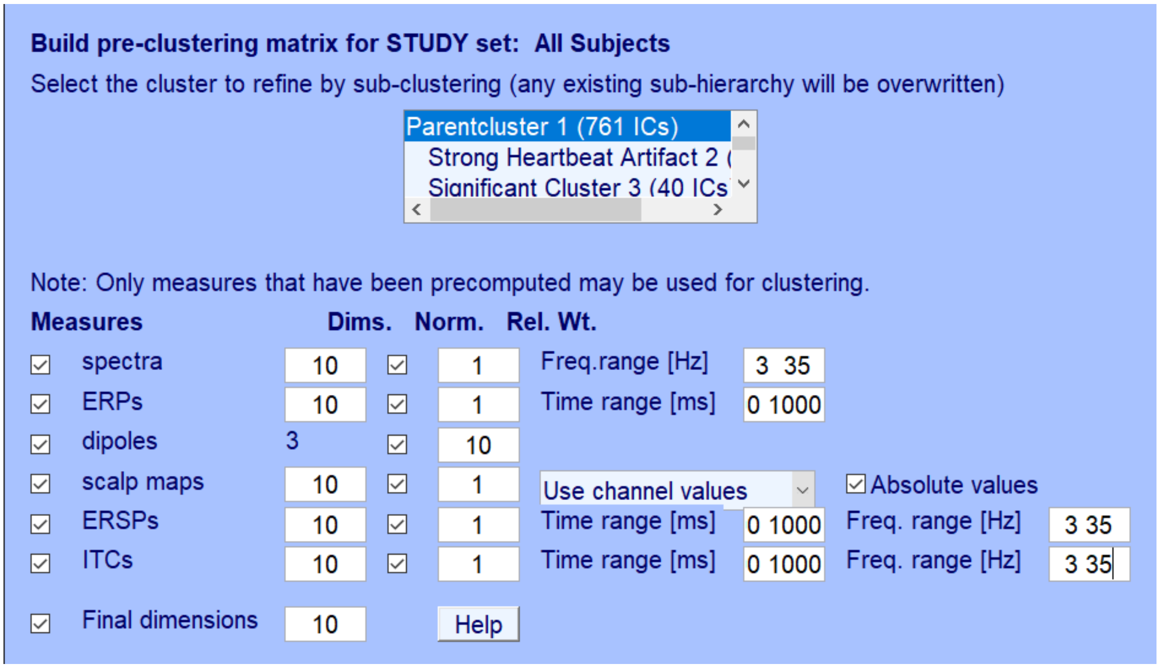
List of measures to precompute

☑ ERPs	Baseline ([min max] in ms)	-200 0
☑ Power spectrum	Spectopo parameters	'specmode', 'fft', 'logtrials', 'off'
☑ ERP-image	ERP-image parameters	'nlines', 10,'smoothing', 10
☑ ERSPs ☑ ITCs	Time/freq. parameters	'cycles', [3 0.8], 'nfreqs', 100, 'ntimes
☑ Scalp maps		

☐ Save single-trial measures for single-trial statistics (beta) - requires disk space
☑ Overwrite files on disk

Figure 8.1: The parameters used for determining component measures for clustering in EEGLAB.

Building the clustering array required choosing data features to use for similarity clus-



Build pre-clustering matrix for STUDY set: All Subjects

Select the cluster to refine by sub-clustering (any existing sub-hierarchy will be overwritten)

Parentcluster 1 (761 ICs)
Strong Heartbeat Artifact 2 (
Significant Cluster 3 (40 ICs

Note: Only measures that have been precomputed may be used for clustering.

	Measures	Dims.	Norm.	Rel. Wt.				
☑	spectra	10	☑	1	Freq.range [Hz]	3 35		
☑	ERPs	10	☑	1	Time range [ms]	0 1000		
☑	dipoles	3	☑	10				
☑	scalp maps	10	☑	1	Use channel values		☑ Absolute values	
☑	ERSPs	10	☑	1	Time range [ms]	0 1000	Freq. range [Hz]	3 35
☑	ITCs	10	☑	1	Time range [ms]	0 1000	Freq. range [Hz]	3 35
☑	Final dimensions	10		Help				

Figure 8.2: The parameters used for preclustering components in EEGLAB STUDY.

tering. For the purposes of my analysis, I reasoned that using all of the data parameters for clustering would produce the most accurate fit. I therefore included the spectra, ERPs, dipoles, scalp maps, ERSPs and ITCs with an equal weighting for each parameter except for the dipoles, whose magnitude was 10 times larger. I used all of the default parameters except for the spectrum, which I expanded to include higher frequencies (i.e. from 3 to 35Hz). Further, I clustered the ERP parameters on the full epoch (i.e. -200 to 1000ms). I included 10 dimensions from each parameter, but the final pre-clustering array was formed using a PCA decomposition to reduce the overall array to 10 total dimensions. These selections are shown in Figure 8.2.

8.2.3 Isolating the Cardiac Field Artifact

Instead of tracking electrode-level ERPs, ICA allowed me to analyze component ERPs and use the EEGLAB STUDY tools for decomposition. This decomposition made the cardiac field artifact visually apparent in ERPs of several components and easy to remove from analysis.

I labelled two components with very strong cardiac field artifacts: Strong Heartbeat Artifact 2 & 13. These ERPs closely resembled the QRS complex and were orders of magnitude larger than the other ERPs. There were three additional components whose magnitudes were comparable to other ERPs, but with a large spike at the 0-time point. I reasoned that these were likely to also include cardiac field artifact and did not appear to be different between the conditions either (Heartbeat Artifact 11, 16 & 17). Figure 8.3 displays these labelled ERPs for the Visual-Only and Audio-Visual trials.

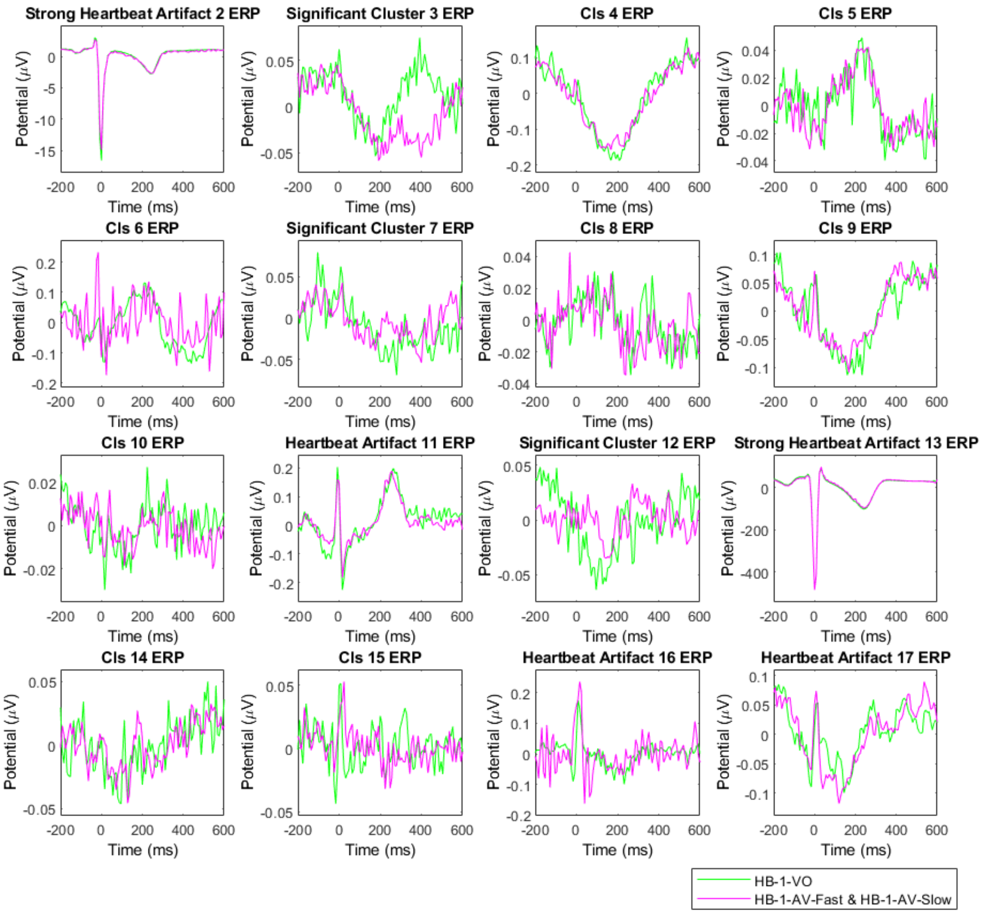


Figure 8.3: ERPs revealed in 16 component clusters. ERPs with the cardiac field artifact are readily identifiable by their greater magnitude and strong deflection at 0ms. Other clusters appear to show significant differences in their component ERPs.

8.3 Results

After isolating the cardiac field artifact, there were three clusters that appeared to have significant differences between the Visual-Only and Audio-Visual ERP components (Significant Cluster 3, 7 and 12). However, Cluster 12 appeared to have a difference earlier than 200ms, which meant that it could not be linked to the interoceptive time window (200-600ms). The two remaining clusters appeared to have significant differences between the Visual-Only and Audio-Visual conditions in the time-window of 200-600ms. I therefore subjected them to statistical testing. To reduce high-frequency variance between the two conditions, I low-passed these ERPs at 10Hz. To handle multiple comparison testing, I used non-parametric cluster-based permutation statistics with a statistical threshold of $p = 0.05$. This statistical procedure has been used in other HEP studies [157, 244, 33, 36]. These two ERPs contained significant regions of difference between the two conditions which are analyzed in more detail analyzed in Sections 8.3.1 and 8.3.2.

8.3.1 Component ERPs

I hypothesized that there would be a difference in the HEP between the Visual-Only condition and the Audio-Visual conditions (H3), in particular that hearing the auditory heartbeats of another person would decrease interoceptive processing, as indexed by a more negative deflection (H3.1). Figure 8.4 displays a comparison of the Significant Cluster 3. There were several portions that met the statistical threshold for difference, mostly in the region of 350ms to 500ms. In this region, the Audio-Visual condition was significantly more negative than the Visual-Only condition.

Figure 8.5 displays a comparison of the Visual-Only and Audio-Visual conditions for Significant Cluster 7. This component had two relatively shorter timepoints that were statistically different, the first was a continuous range between 200 and 225ms, and the second in a region around 525 to 550ms. In this region, the Visual-Only condition was significantly

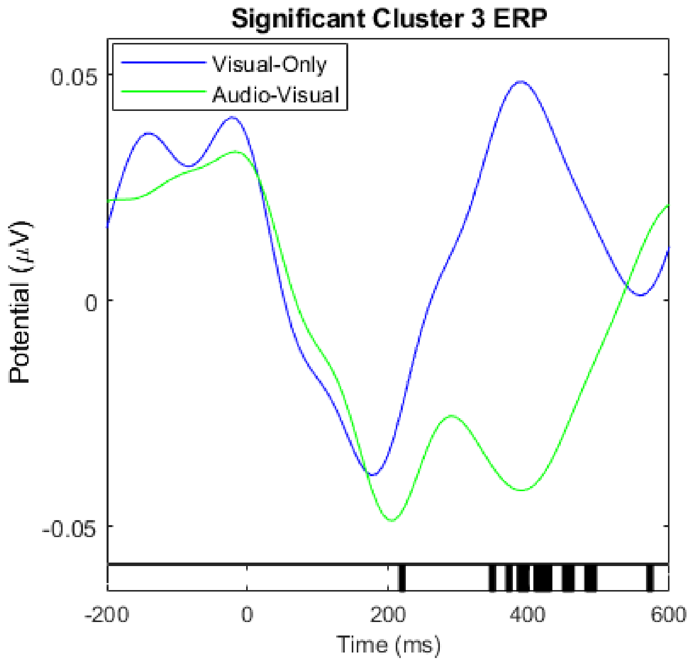


Figure 8.4: The Visual-Only condition had a significantly higher ERP in between 350ms to 500ms in Significant Cluster 3.

more negative than the Audio-Visual condition.

8.3.2 Component Dipoles

Many different locations have been reported for the HEP, largely frontal and central in channel-level ERPs. Although I did not make any hypothesis as to the location of the HEP, I decided to explore the dipole locations of the cluster centroids for these significant ERPs. In general, EEG is not an ideal modality for analysis of functional brain-areas. However, by combining analysis methods across subjects, I could determine the mean location for several similar components, therefore achieving a more precise estimate of cortical location. I also interpret the mean cluster locations in terms of Broadmann Areas, which are larger areas of the cortex surrounding the TAL coordinate.

Figure 8.6 displays the dipole components clustered with Significant Component 3. The location of the centroid of this cluster was X-TAL: -26, Y-TAL: 68, Z-TAL: 5, resolved

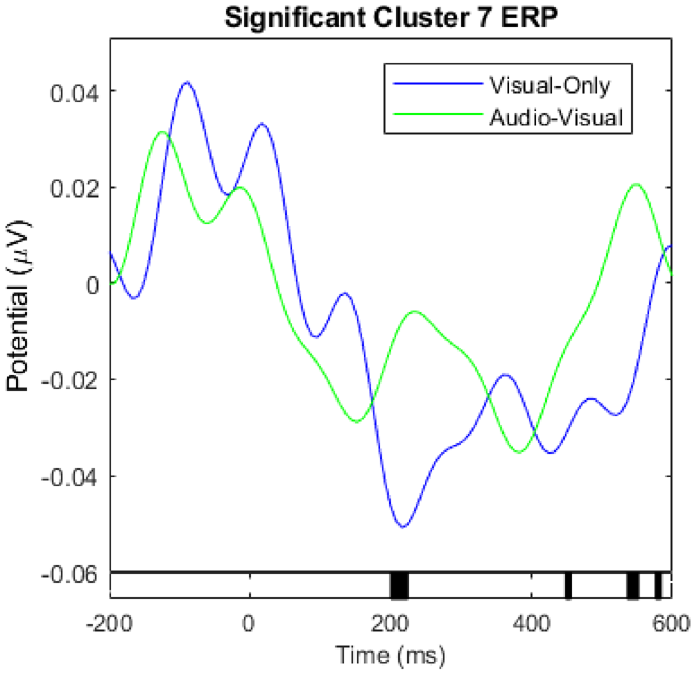


Figure 8.5: The Audio-Visual condition had a significantly more positive ERP in between between 200ms to 225ms and 525 to 550ms in Significant Cluster 7.

down to 7.82% RV. This dipole localized most closely to Broadmann's Area 10, which is the left anterior prefrontal cortex.

The anterior prefrontal cortex is involved in complex executive function and especially tasks integrating more than one cognitive process in the pursuit of a behavioral goal [245, 246]. In the context of this experiment, this area might support the task of determining what the virtual person was experiencing. The task required remembering four possible words, reasoning about the possible choices, and integrating these choices with this information from visual and auditory signals.

Figure 8.7 displays the dipole components clustered with Significant Component 7. The location of the centroid of this cluster was X-TAL: -20, Y-TAL: -53, Z-TAL: 68, resolved down to 6.96% RV. This dipole localizes most closely to Broadmann's Area 7, which is part of the superior parietal cortex.

The part of the parietal cortex occupied by Broadmann Area 7 has been implicated in

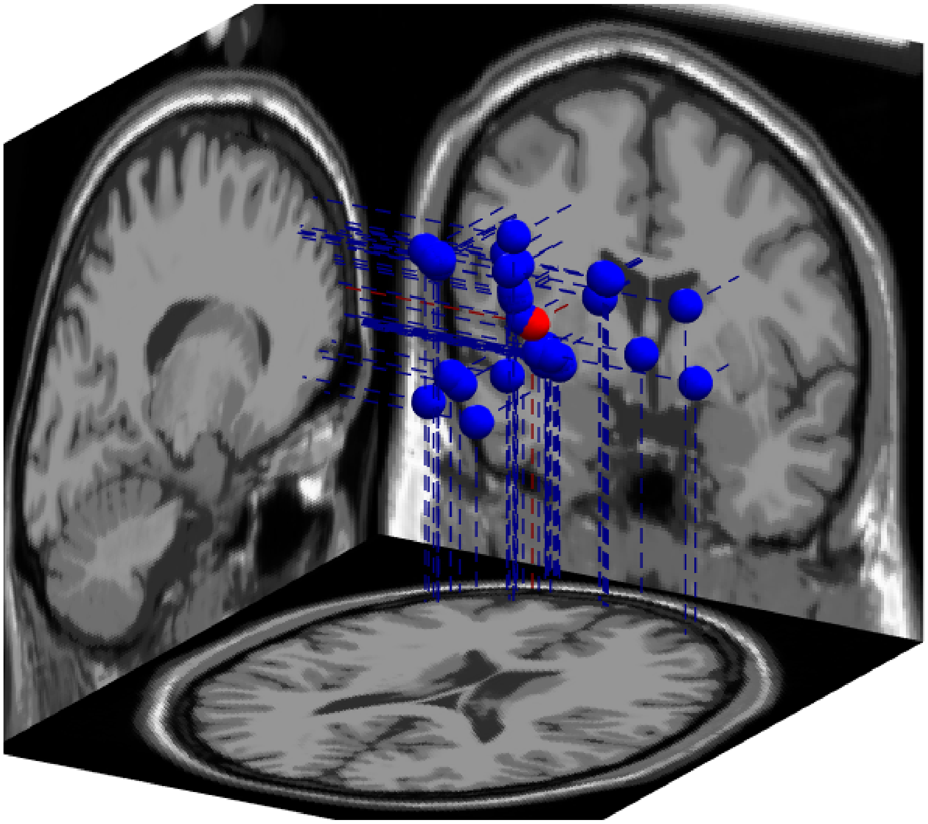


Figure 8.6: The dipole of Significant Cluster 3 localized to Broadmann's Area 10 (X-TAL: -26, Y-TAL: 68, Z-TAL: 5).

a variety of high-level processing tasks, especially those having to do with visuo-motor coordination and language [247]. The function with respect to this task is not well-defined. However, in could be due to the coordination of several modalities, specifically visual, linguistic, motor and auditory. Future work may reveal the roots of the relationship and differences between these two clusters.

8.3.3 Analysis

To date, research on the HEP has been characterized by a diversity of experimental designs and methodologies, and fundamental knowledge about its origins are still developing [35]. This exploratory study was the first to study the effects of an exteroceptive auditory signal attributed to the affective state and cardiac physiology of another person. Further, while many studies apply statistics to scalp-level differences, ours utilized component clustering

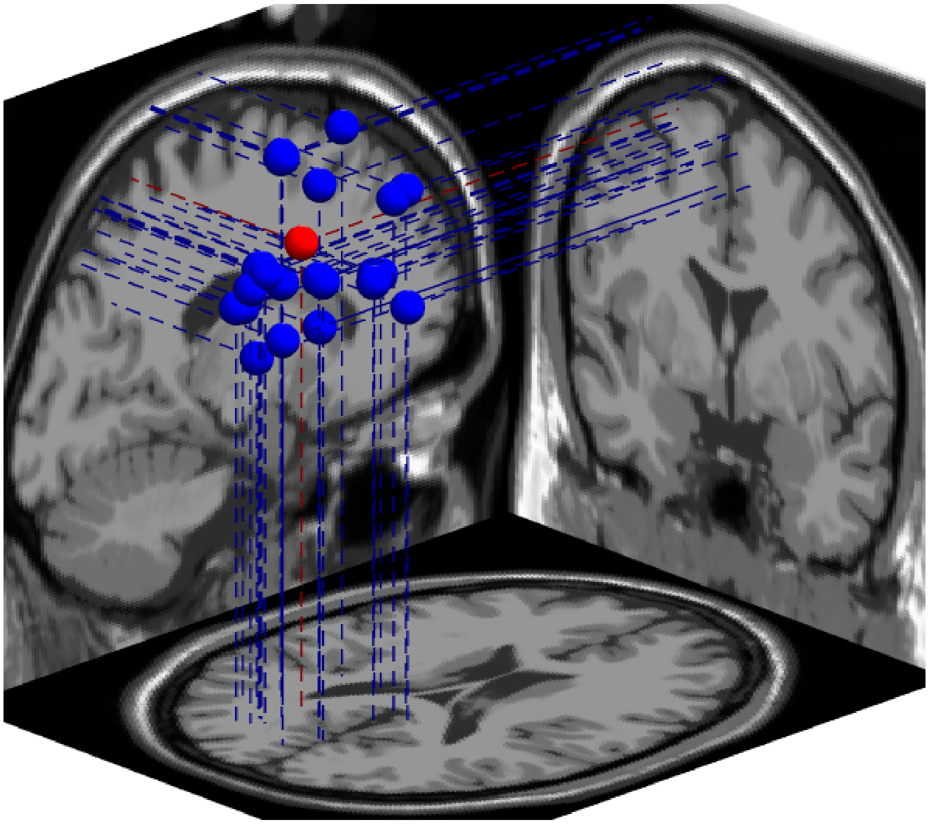


Figure 8.7: The dipole of Significant Cluster 7 localized to Broadmann's Area 7 (X-TAL: -20, Y-TAL: -53, Z-TAL: 68).

and dipole fitting to estimate the cortical locations.

Prior work has also demonstrated a diversity of cortical locations for the HEP [35]. As an exploratory EEG study, our analysis of the cluster locations should be supported by future work. However, Cluster 3 seems to be related to the findings presented in Section 8.1.1, which suggests that a more negative frontal HEP would be associated with a i) decrease in interoceptive (heartbeat) attention and ii) increase in attention to the feeling states of others, supporting our original hypothesis (H3.1).

8.4 Conclusions

I was able to identify HEP components that were significantly different between the Visual-Only and Audio-Visual conditions. In particular, the Visual-Only condition had a significantly more positive frontal component ERP than the Audio-Visual condition, which I attributed to a decrease in interoceptive attention due to auditory heartbeats. This dipole localized to the anterior prefrontal cortex and is attributed to the goal of the task. A second component ERP had a significantly more negative component ERP, which was out of phase with the other cluster and localized to the superior parietal cortex. These may be attributable to cortical differences in the processing of the afferent cardiac signal. Future work will provide more clarity to the functional differences of the HEP in these two regions.

CHAPTER 9

DISCUSSION

9.1 H1: Changes in Empathic State

Given the current understandings of empathy presented in Section 3.1.1, I quantified changes in empathic state along two dimensions: cognitive and affective. I predicted that hearing the heartbeat of another person would change the listener's cognitive empathy (H1.1) and increase their affective empathy (H1.2), which I measured these with my RMET Change and Feeling Strength Z-Score variables respectively.

9.1.1 H1.1: Change in Cognitive Empathy

To measure changes in cognitive empathy, I compared participant's responses to a modified version of the Reading the Mind in the Eyes Task to their responses in a pre-trial baseline. Compared to their baseline choices, participants changed their responses significantly more often when the stimulus contained heartbeats, rejecting the null for H1.1 that heartbeats would not change cognitive empathy. Upon analysis of the heartbeat tempo, I found that participants changed their responses in the RMET more often when the auditory heartbeat stimulus was fast than when it was slow, and when it was incongruent compared to when it was congruent.

With respect to cognitive empathy, these results point to a few important conclusions. Primarily, a rhythmic auditory stimulus attributed to the heartrate of another person can influence affective perception. This fact is especially evident in incongruent audio-visual stimuli, where participants were more likely to change their responses due to an incongruent heartbeat tempo. Given the strength of facial expressions in the perception of another person's affect, these results position tempo as an affective cue with surprisingly strong salience. Tempo can complement and re-direct the interpretation of affective visual signals, similar to the ways that music can alter the perception of visual scenes in movies and games. My results also showed that cognitive empathy was more likely to change when the heartbeat was fast, meaning that seeing a person and hearing a fast heartbeat is more likely to change one's perception of their affect than hearing a slow heartbeat. This sensitivity to heartbeat tempo has important implications for heartbeat sharing—one is more likely to produce an affective change in a receiver with fast heartbeats.

An important lingering question is whether or not listeners' affective perspective changed even when they did not create a measurable change in their RMET score. It could be that there were changes in their perspective that were not measurable due to the design of my test (i.e. counting changes in the selected emotion label). Section 3.3.5 details the strong effects that music has on perception, memory and affective association of visual scenes. It seems plausible that affective perspective was altered in all cases, but only some cases where these changes observable. For future work, I hypothesize that a more sensitive approach to measuring cognitive empathy would reveal changes in cognitive empathy due to heartbeats that were not observable in this experiment design.

9.1.2 H1.2: Increase in Affective Empathy

To measure changes in affective empathy, I utilized a seven-point Likert scale that asked, "How well did you feel what they were feeling?" at the end of every trial. Section 6.4 presented my results. I found that the audio-visual condition was significantly greater than visual-only condition, rejecting the null for H1.2, that heartbeats would not increase affective empathy.

My experiment design allowed an even more nuanced analysis of the effect of auditory heartbeat through comparison of the audio-only condition as well. Through multiple comparison testing, I found that there was no significant difference between this condition and the visual-only condition. This is a surprising result because it means that the ability to feel what another person was feeling was comparable between hearing their heartbeat without seeing them and seeing their eyes in silence. This result echoes previous work that had found no significant difference in intimacy between hearing someone's heartbeat (audio-only) and direct eye contact (visual-only) [71]. Leveraging the results from cognitive empathy, these results further the idea that the tempo of the heartbeat and expression in the eyes are affectively meaningful signals that may have equal power to influence affective empathy.

When analyzing the effects of congruency, I found a significant difference between the congruent and incongruent pairings. Namely, the congruent pairings had significantly higher ratings of affective empathy than incongruent pairings. This result is especially intriguing considering that there were significantly more changes in cognitive empathy in the audio-visual incongruent condition, and points to an interaction between these forms of empathy in this condition. Specifically, for audio-visual incongruent trials, the change in cognitive empathy may be associated with a decrease in affective empathy. One explanation for this result would be that when the audio-visual stimuli did not match each other, participants found it more difficult to "feel what they were feeling." They might have been less sure what they were feeling. On the other hand, this result might also speak further to the idea presented in Section 9.1.1, namely that even though there were no changes in cognitive empathy in the congruent condition, there were still changes in empathy which could be measured using my affective empathy measure.

My experiment design also allowed us to study tempo and its interaction with modality in the audio-only and the audio-visual stimulus. Specifically, I found no difference in affective empathy between fast and slow heartbeats when the eyes were visible, but when the eyes were not visible, the slow heartbeat had significantly lower ratings of affective empathy. This result recalls the sensitivity of cognitive empathy to heartbeat tempo that I found in my cognitive empathy measure (albeit in the audio-visual condition), namely that faster heartbeats produced more changes in cognitive empathy. From these results, it would appear that there is an unequal empathic response between fast and slow heartbeats, generally with faster heartbeats being associated with more changes in cognitive empathy and higher levels of affective empathy. Furthermore, these results seem to depend upon whether or not the eyes stimulus is present.

These results have important implications for the applications of auditory heartbeat sharing presented in Chapter 2. One important result is that hearing someone's heartbeat without seeing them may have comparable effects on affective empathy as seeing their eyes. This could be useful in cases of situational, temporary or permanent blindness. Speaking to the ability of inclusive design to benefit even those without a disability [248], I find that adding auditory heartbeats increases affective empathy even when listeners can already see the person. Another important design consideration is the way that empathic responses depend upon tempo. If the person can be seen, higher heartbeat tempos might be associated with more changes in cognitive empathy than slow heartbeats in spite of having equal amounts of affective empathy. If the person cannot be seen, faster heartbeats might be associated with greater affective empathy.

9.1.3 H1.3: Dispositional Empathy Correlations

I also hypothesized that listener's empathic traits would impact their empathic response and reported several correlations between participant's empathic response to my stimuli and their empathic traits, rejecting the null for H1.3.

Of the many indices that I measured, I found a significant positive correlation between participant's scores on the Emotional Contagion Scale [224] and their responses to the affective empathy question. In Section 3.3.3, Emotional Contagion was presented as a prominent pathway to induced emotion in music [3, 50] with clear relation to the affective component of empathy [22, 188]. The correlation I observed confirms my expectation, namely that people with higher emotional contagion reported higher responses to "How well could you feel what they were feeling." This result also supports the validity of my second question as a measure of the emotional contagion component of affective empathy.

In a similar vein, I found a significant positive correlation between participants IRI-Fantasy Score and their responses to the affective empathy question. I attributed this correlation to the ability of people with high scores on the IRI-Fantasy subscale to imaginatively put themselves into fictional situations and empathize with fictional characters. It is possible that by using “virtual” or “imagined” people in my experiment may have catered to those with high IRI-Fantasy scores. If so, then a different experiment with more “realistic” people might remove this response bias.

Finally, I found that people that scored higher on their baseline RMET were subsequently less likely to have a measurable change in cognitive empathy during the test. This may speak to a relatively more fixed perspective for those who did well on the RMET baseline. For those that did poorly, further analysis might reveal if they became more accurate (in the congruent condition), or if they were simply more susceptible to changes in perspective due to not having a clear idea of what the person was experiencing in the baseline. If the latter is true, then this might speak to the power of auditory heartbeats an intervention for people who struggle to identify visual affect. It might be used as a cue to help them identify the “correct” affect in another person. Further analysis could determine if people who scored poorly on the RMET baseline became more correct for “congruent” audio-visual stimuli later in the experiment.

9.2 H2: Changes in Physiology

Although there are many ways of sensing physiological change, I focused my analysis on listener’s heartrate. This analysis allowed us to study the changes in participant’s heartrate due to perceiving the heartrate of another person as expressed through heartbeat tempo.

9.2.1 H2.1: Decrease in Heartrate

Prior work has demonstrated the capacity of music to impact physiology as measured through heartrate (Sec. 3.4.2). By comparison to this prior work, my stimuli are unique because they are attributed to the affect of another person, study the effect of tempo in isolation, and are comparatively short—lasting only 20s. In spite of these differences, I found changes in heartrate which I attributed to the auditory stimuli, its tempo, and participant's reported affective empathy.

I found was that exposure to the auditory heartbeat resulted in a significant decrease in heartrate, rejecting the null hypothesis of H2.1. These heartrates were significantly below participant's pre-trial baseline heartrate, and furthermore, there was no significant change in heartrate for the visual-only (silence) condition. This indicates that auditory heartbeats were physiologically active in a way that was not found in the visual-stimuli alone. Furthermore, the physiological activation of auditory heartbeats was likely parasympathetic—as measured by a rapid decrease in heartrate. Although the decrease in heartrate was greatest for the audio-only condition, it is possible that the relaxation response contributed to the empathic effects found in the audio-visual stimuli. If a decrease in heartrate did lead to higher affective empathy, it might be because connecting empathically to another person is facilitated by a parasympathetic activation signaling relaxation, calm and safety.

Within a global context of physiological relaxation and a decrease in heartrate, congruent audio-visual stimuli were found to have relatively higher heartrate than incongruent audio-visual stimuli. This means that when the arousal-level in the eyes matched the arousal level represented by the tempo of the auditory heartbeat, the listener's heartrate was higher relative to the same presentation with a heartbeat that was the opposite in arousal (e.g. fast→slow, slow→fast). These results point to a complex physiological interaction between the heartbeats, and their affective relationship to the visual stimuli. There may be contrasting sympathetic and parasympathetic activations at play.

9.2.2 H2.2: Heartrate Entrainment

Based upon prior research and my piloting, I hypothesized that there would be autonomic physiological entrainment to the tempo of the auditory heartbeat. However, I found no significant differences between slow and fast auditory heartbeats in the audio-only or the audio-visual conditions across all trials. Therefore, my data do not reject the null hypothesis for H2.2.

Because previous studies had shown entrainment, I reasoned that my lack of effect was be attributable to fatigue and narrowed my analysis on the first 25% of trials. In this analysis, I found a difference in heartrate consistent with predictions of autonomic physiological entrainment to tempo, but only in the audio-only condition. Because I did not find it in the audio-visual condition, these results highlight a possible interaction with modality. I hypothesize that in the audio-only condition, listener's attention was directed more fully to the auditory stimulus, while in the audio-visual condition, it was split with the visual stimulus. If this is true, then autonomic physiological entrainment to tempo would depend upon auditory attention. This could be tested in future work by limiting the experiment to audio-only stimuli, using fewer trials (to reduce fatigue), and a between subjects design with one group performing an unrelated task (e.g. math), and another group performing a focused listening task.

9.2.3 H2.3: Affective Empathy

I hypothesized that high affective empathy would be associated with a greater heartrate than low affective empathy (H2.3). My results rejected the null hypothesis for the audio-only condition, but not the visual-only or audio-visual conditions. Within the audio-only condition, high affective empathy trials were associated with higher heartrates than low affective empathy trials. Upon analysis of the fast and slow tempi, I found that that high affective empathy created a relatively higher heartrate in the audio-only fast condition, but no significant difference in the audio-only slow condition. Altogether, these results support a complex physiological activation of heartbeats due to tempo and affective empathy. Because these results were not present in the audio-visual condition, there is further evidence that full attention to the auditory stimulus is required to see differences in heartrate. These results also support a theory that within a general parasympathetic activation due to the heard heartbeat, higher tempos and greater affective empathy may be associated with a contrasting sympathetic activation, resulting in a higher heartrate.

When examining effects on the first 25% of trials in the experiment, I found additional effects. In the visual-only condition, high self-reported empathy was associated with a significantly lower heartrate than low self-reported empathy. By contrast to the observations of the auditory heartbeats, this indicates that higher levels of affective empathy were associated with lower heartrates, as opposed to higher heartrates in the auditory conditions. The difference between these two effects is interesting and might indicate differences in how participants were gauging their affective empathy in the visual-only and audio-only trials. Auditory heartbeats generally created a decrease in heartrate for listeners and were associated with increases in affective empathy. It could be that in the multimodal context of this experiment, listeners were associating more relaxed physiology with higher levels of empathy.

9.3 H3: Change in HEP

9.3.1 H3.1: Negative HEP

Previous work that had demonstrated that there was an increased positivity in the HEP during attention to one's own heartbeat, and more negative HEP in response to affective judgements of others. I reasoned that hearing the heartbeat of another person would diminish interoceptive attention and create a more negative HEP (H3.1). Using Independent Component Analysis (ICA), component clustering and non-parametric statistics, I found two components with significant differences in the time-range of 200ms to 600ms, which has been associated with the HEP. The more prominent of these components localized to the anterior prefrontal cortex and the audio-visual condition was associated with a more negative ERP compared to the visual-only condition.

Given the similarity of the auditory heartbeat to the listener's heartbeat and the empathetic listening context, I theorized that the auditory heartbeat functioned as an "exteroceptive" stimulus, which directly conflicted with listener's own interoceptive processing. In essence, by attending to the heartbeat of another person and trying to determine what that person might be experiencing, listener's subconscious attention to their own physiological processing was diminished. If this were true, this type of listening intervention might be helpful for people whose attention to their own internal physiological state is too great, such as occurs in the self-referential thought patterns of depression [249]. In this case, empathic listening to the heartbeats of another person might help train the person to orient their attention to the exteroceptive signals, and through training, might help them reduce interoception and change thinking patterns more generally.

CHAPTER 10

CONCLUSION & FUTURE WORK

10.1 Conclusion

10.1.1 Core Contribution

This research demonstrated that auditory heartbeats can increase affective empathy and change listeners' cognitive empathy. I attribute these effects to the affective content of the heartbeat tempo, and its interaction with the visual stimuli. Through analysis of listeners' heartrates, I found that listening the heartbeats was associated with a significant decrease in listener heartrate. However, other factors such as heartbeat tempo, audio-visual congruency and affective empathy created additional differences, pointing to more complex physiological activations. I also found significant differences in two HEP components that localized to the anterior prefrontal cortex and superior parietal cortex. The frontal component was significantly more negative between 400-450ms, which I attribute to an exteroceptive attentional shift engendered by empathic listening to the heartbeat.

10.1.2 Broad Impact

Empathy is a fundamental capacity that facilitates social connection and understanding [250], but empathetic connections are not always readily accessible or easy to maintain [251]. This research demonstrated that hearing the auditory heartbeats of another person can alter and enhance empathetic connections between people at behavioral and neurophysiological levels. Technologies that share heartrate information through auditory heartbeats can benefit from the results of this work, especially for understanding the effects of heartbeats relative to silence, the effects of tempo, and the effects of audio-visual pairings. One particularly fruitful area for future applications is as an intervention for affect perception in autism. In this population, heartbeat tempo could be used as a proxy for affective arousal, relying on similar associations found in the tempo of music.

10.1.3 Intellectual Merit

My research arises in a broader context of understanding the links between musical tempo, empathy and neurophysiology (Chp. 3). Music is a fundamentally social medium, which facilitates group affiliation, cohesion, cooperation and empathy. Although prior research has suggested that empathy is active in music listening and contributes to the induced emotions in music, only one study to date has experimentally manipulated empathic state. To this line of work, I contribute an experimental method that attributes musical tempo to the affective state of another person. This allowed me to characterize effects of exposure to auditory heartbeats on empathic state and neurophysiology, contributing to both fundamental science and application research. To my knowledge, I present the first HEP study to use auditory heartbeats and demonstrate that empathic attention to this exteroceptive signal produces effects consistent with reduced cardiac cortical attention.

10.2 Future Work

10.2.1 Other Sounds

An important qualification of the present research was that the listeners imagined that the auditory heartbeats they heard came from the heartbeats of another person. However, there was not a "real" person, or a "real" heartbeat. It is therefore possible that these empathic effects could be generalized to other visual and auditory representations. For example, visual faces could be swapped with emojis, and the auditory heartbeat could be swapped with other beat-like sounds.

This later question is particularly interesting for future music research because it would provide a methodology for understanding the effects of listening in an empathic state to music more generally. One simple experiment would be to test if listening to a completely different sound (e.g. a triangle) could produce similar changes in empathy or neurophysiology. If it did not, there would be something special about the rhythmic heartbeat in terms of its structure or listeners' cognitive associations. Towards this matter, I predict that the results extend to empathizing with the beat of music more generally.

10.2.2 Effects of Empathy vs. Non-Empathy

Important questions arise relating to whether the physiological effects I measured require a listener to deliberately imagine that the sound as coming from another person (as in this experiment), or if it is sufficient to simply be exposed (without conscious attention) to a repetitive auditory stimulus of similar tempi. If the effect was specific to the empathy condition, then I would know that the effects are due to empathy alone. However, if effects were shown in a case of non-empathy, this would indicate that the effects were due to the underlying acoustic structure. For example, a participant could listen to the same acoustic stimulus as if it were a clock, and objectively count the beats. The heartbeat could also be played in the background while the participant does a completely unrelated task like math or other puzzles. To this end, I predict that the mere presence of the rhythmic acoustic stimulus (i.e. a musical "beat") can alter a participant's physiology, but empathic/attuned listening will create changes in empathy and even greater changes in physiology.

10.2.3 Relation to Meter

This work explored variations in tempo as a fundamental musical variable. For all given purposes, the music used in this study did not have a hierarchical rhythm such as is found in many world musics. However, metrical hierarchies are common aspects of music more generally, and may contribute to structurally-oriented empathic listening mechanisms. Therefore, another extension of this work would be to introduce meter into the auditory stimulus by repeatedly emphasizing a particular beat in a group. If significant effects were found, this would have important design implications for auditory heartrate sharing, especially concerning what acoustic cardiac parameters are affectively salient [55].

10.2.4 Takeaways for Performers & Composers

Section 3.2 presented a broad overview of the ways that empathy has formed a crucial component of the contemporary landscape of music listening. Composers or performers that express their music in such a way as to promote empathy with them or their music may be more successful commercially. I therefore recommend an empathic perspective to composition and performance. For example, when composing a piece, a composer might begin by imagining the heartbeat of a virtual person they are creating through their composition. Performers can benefit from establishing a person/persona and animating the music as if it were a body, person or group in a scene and context. When music is composed and performed in this way, listeners will be able to use their capacity for empathy to engage with the music.

10.2.5 Improvements to the Experiment Current Design

The Active Empathic Listening Scale [252] is a scale designed to measure a participant's disposition to listen in an active and empathetic manner to another person's speech. Although this scale was made in the context of verbal communication, because this test also involved empathic listening, there might be a correlation between participant's behavioral responses and their scores on this scale.

I hypothesized that listener's HEP would become more negative in response to the auditory heartbeat of another person. Interoceptive perception, accuracy and attention is associated with a more positive HEP. In the future, this test should be added to the pre-survey questionnaires. It is possible that people who have higher interoceptive abilities would have been differently affected by the auditory heartbeats than those with poor interoceptive abilities.

Appendices

APPENDIX A

PARTICIPANT INSTRUCTIONS

The following are the instructions given to each participant at the start of the experiment. The instructions were given verbally, and a copy of the instructions was left in a readily available location on the experiment desk during the study.

Instructions for Heartbeat Study

This is a study on the effect of listening to other people's heartbeats on empathy. There will be **144 trials** broken into 12 blocks with breaks in between. Each trial will last about 30 seconds and will have two questions lasting 20s and 10s respectively.

Question 1

The first question is, "What is this person feeling?" You will be presented with four choices, and will need to choose one to continue. Sometimes it will be easy, sometimes it will be hard. There is not a wrong or right answer, only the answer that you think is best. If you ever don't know the definition of a word, you can just hover your mouse over it, and a definition will pop up.

Sometimes you will be able to see the eyes of the person, and sometimes you won't. Sometimes you will be able to hear their heartbeat and sometimes you won't. The rest of the time, you will both see their eyes and hear their heartbeat at the same time. When that happens, the heartbeat you are hearing is coming from the same person whose eyes you see.

If you answer early, continue looking, listening and imagining their feeling until the next screen.

Question 2

The second question is, “How well did you feel what they were feeling?”

For example, imagine you said the person in the first question was angry, in this question you would rate how well you could *feel* their anger. Kind of like watching a character in a movie. If you were able to feel it so well that it was almost like you were feeling it yourself, then you would mark a 7: *Extremely well*. If you answered, but did not personally feel what they were feeling, you would mark a 1: *Not well at all*.

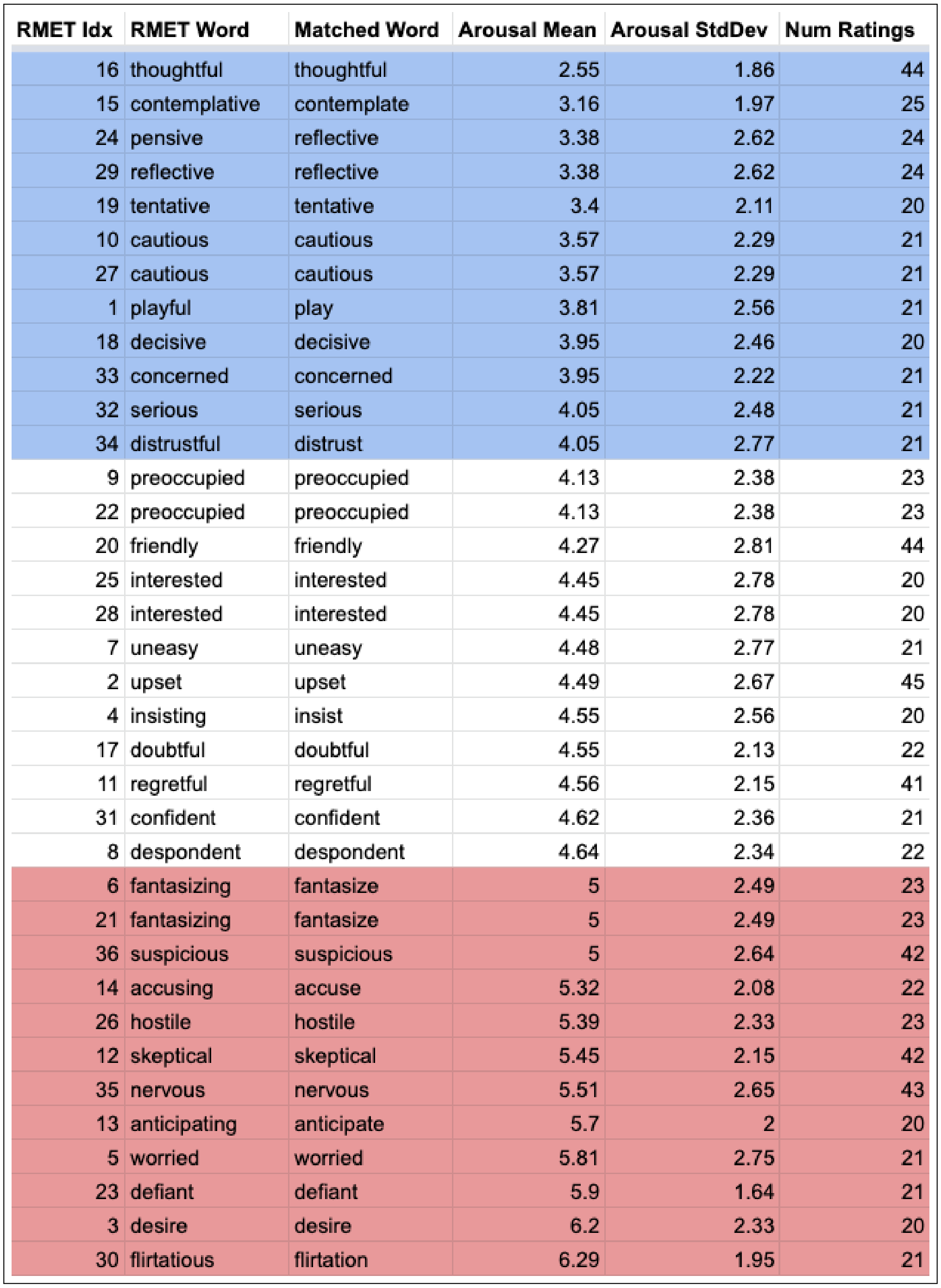
Like the first question, there is no wrong or right way to respond, except for what most accurately reflected your state during Q1. Once you have chosen, you can relax and wait for the remainder of 10 seconds to pass. When you are ready to start the next trial, click Next.

Breaks

You will get a break roughly every 6 minutes (12 trials). I recommend using them. People have told me that answering the questions can get tiresome, and you will finish early either way. You can also help yourself to some **candy**. But please finish eating before the next trial because your jaw and neck muscles will obscure the EEG signal.

APPENDIX B

RMET AROUSAL GROUPING



RMET Idx	RMET Word	Matched Word	Arousal Mean	Arousal StdDev	Num Ratings
16	thoughtful	thoughtful	2.55	1.86	44
15	contemplative	contemplate	3.16	1.97	25
24	pensive	reflective	3.38	2.62	24
29	reflective	reflective	3.38	2.62	24
19	tentative	tentative	3.4	2.11	20
10	cautious	cautious	3.57	2.29	21
27	cautious	cautious	3.57	2.29	21
1	playful	play	3.81	2.56	21
18	decisive	decisive	3.95	2.46	20
33	concerned	concerned	3.95	2.22	21
32	serious	serious	4.05	2.48	21
34	distrustful	distrust	4.05	2.77	21
9	preoccupied	preoccupied	4.13	2.38	23
22	preoccupied	preoccupied	4.13	2.38	23
20	friendly	friendly	4.27	2.81	44
25	interested	interested	4.45	2.78	20
28	interested	interested	4.45	2.78	20
7	uneasy	uneasy	4.48	2.77	21
2	upset	upset	4.49	2.67	45
4	insisting	insist	4.55	2.56	20
17	doubtful	doubtful	4.55	2.13	22
11	regretful	regretful	4.56	2.15	41
31	confident	confident	4.62	2.36	21
8	despondent	despondent	4.64	2.34	22
6	fantasizing	fantasize	5	2.49	23
21	fantasizing	fantasize	5	2.49	23
36	suspicious	suspicious	5	2.64	42
14	accusing	accuse	5.32	2.08	22
26	hostile	hostile	5.39	2.33	23
12	skeptical	skeptical	5.45	2.15	42
35	nervous	nervous	5.51	2.65	43
13	anticipating	anticipate	5.7	2	20
5	worried	worried	5.81	2.75	21
23	defiant	defiant	5.9	1.64	21
3	desire	desire	6.2	2.33	20
30	flirtatious	flirtation	6.29	1.95	21

Figure B.1: The arousal ratings for answers in the RMET matched to words from [228]. These ratings were used to create high and low arousal groups for the visual stimuli as described in Section 5.7.1.

APPENDIX C

EXPERIMENT & STIMULUS CODE

Supercollider was used to model and control the heartbeat sound, to present participants with the eyes stimulus, collect their responses, and send OSC messages for synchronization with the EEG/ECG recording.

Listing C.1: Heartbeat Sample Controller

```
// Boot the server
s.boot;

// Load the heartbeat sample
a = Buffer.read(s, ˜curDir ++ "/Heartbeat/20190124_Heartbeat.wav");

// Make a synthdef for playing the sample
SynthDef(\playHeartbeat, { arg mul;
    // An envelope for controlling the amplitude of the sample
    var env = EnvGen.kr(Env.linen(attackTime: 0.01, sustainTime: 1, releaseTime:0.01));
    // A Buffer playback object
    var playBuf = PlayBuf.ar(2, a, doneAction: 2) * env * 0.5;
    // Send it out through the soundcard
    Out.ar(0, playBuf ! 2)
}).send(s);

// Make a function for playing the heartbeat sample at any bpm.
˜playHeartbeatAtBPM = { arg bpm;
    Task( {
        if (bpm > 0, {
            inf.do( {
                // Randomness decreases with BPM
                var randAmount = 40 / bpm;
                // A gaussian centered at zero with deviation determined by bpm
                var rand = 0.gauss(0.08 * randAmount);
                // The amplitude of the sound is scaled by this value
                var mul = 0.8 + (rand * 10 / randAmount); // the amplitude value

                // play the heartbeat
                Synth(\playHeartbeat, [\mul, mul]);

                // The wait time in between sample triggering.
                ((1/bpm)*60+rand).wait;
            } );
        } );
    } ).play;
};

// This will play the heartbeat sound at 80BPM
```

```
~example = ~playHeartbeatAtBPM.(80);

// This will stop it
~example.stop;
```

APPENDIX D

DATA SYNCHRONIZATION CODE

Python was used in order to synchronize data from the ActiChamp amplifier with the experiment running in SuperCollider. The Supercollider experiment would send OSC messages over the local network to Python, which would format and send them as LSL Markers to the LSLRecorder program. This program was simultaneously receiving the data from the ActiChamp, thus synchronizing the experiment markers with the EEG & ECG data.

Listing D.1: Python OSC Message to LSL Marker

```
#!/usr/bin/env python3
# This code uses pylsl to open an LSLMarker connection and send markers. It
# receives the markers from Supercollider by using pyOSC to set up a OSCServer
# listening on port 7110. Supercollider then sends messages to this port.

from OSC import OSCServer
import sys
from time import sleep

from pylsl import StreamInfo, StreamOutlet

server = OSCServer( ("localhost", 7110) )
server.timeout = 0
run = True

# Make your pylsl connection
info = StreamInfo(’LSL Marker Stream’, ’Markers’, 1, 0, ’string’, ’myuidw43536’)

# next make an outlet
outlet = StreamOutlet(info)

# this method of reporting timeouts only works by convention
# that before calling handle_request() field .timed_out is
# set to False
def handle_timeout(self):
    self.timed_out = True

# funny python’s way to add a method to an instance of a class
import types
server.handle_timeout = types.MethodType(handle_timeout, server)


def user_callback(path, tags, args, source):
    # which user will be determined by path:
```

```
    # we just throw away all slashes and join together what’s left
    #print "hello"
    msg = args[0]
    print msg
    outlet.push_sample([str(msg)])

server.addMsgHandler( "/OSC-Marker-Stream", user_callback )

def quit_callback(path, tags, args, source):
    # don’t do this at home (or it’ll quit blender)
    global run
    run = False

# user script that’s called by the game engine every frame
def each_frame():
    # clear timed_out flag
    server.timed_out = False
    # handle all pending requests then return
    while not server.timed_out:
        server.handle_request()

# simulate a "game engine"
while run:
    sleep(0.001)
    each_frame()

server.close()
```

APPENDIX E

MATLAB CODE FOR EEG CLEANING, EPOCHING, DECOMPOSITION

Listing E.1: The Makoto Pipeline we used for cleaning our data.

```matlab
% The purpose of this function is to run Makoto's pipeline
function EEG = runMakotosPipeline(EEG)

% This is the so-called Mokoto Pipeline (MW 2019)
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% LOAD / FORMAT DATA %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Specify channel locations ( we need this for channel cleaning)
EEGLABroot = [fileparts(which('eeglab'))];
ElectrodePositionPath = [EEGLABroot '/plugins/dipfit2.3/standard_BESA/standard-10-5-cap385.elp'];
EEG=pop_chanedit(EEG, 'lookup', ElectrodePositionPath);

% % We are keeping the EKG and Audio channels, which will aid in decomposition.
% NOTE: We added events based upon the Audio & EKG in a previous step
% EEG = pop_select( EEG,'nochannel',{'EKG' 'Audio'});

% The previous command sorted the events for us, so the first event is the
% start of the data, last event is the end of the data. Add a buffer at the
% beginning and end due to edge artifacts of filtering.
startSample = EEG.event(1).latency - (10 * EEG.srate);
endSample = EEG.event(end).latency + (10 * EEG.srate);
EEG = pop_select( EEG,'point',[startSample endSample] );

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%% RESAMPLE / CLEAN  %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Downsample to 250 Hz
EEG = pop_resample( EEG, 250);

% Highpass filter the data at 1.5 (Makoto Recommends 1-2Hz):
% Mike Cohen recommends 0.5, we use 1
EEG = pop_eegfiltnew(EEG, [], 1, 550, true, [], 0);

% Remove line-noise using cleanline
EEG = pop_cleanline(EEG, 'bandwidth',2,'chanlist', [1:EEG.nbchan] , ...
    'computepower',1,'linefreqs',[60 120] ,'normSpectrum',0,'p',0.01, ...
    'pad',2,'plotfigures',0,'scanforlines',1,'sigtype','Channels','tau', ...
    100,'verb',1,'winsize',4,'winstep',1, 'VerboseOutput', false);

% Remove bad channels (code from
```

```
% https://sccn.ucsd.edu/wiki/Makoto’s_useful_EEGLAB_code, 12/7/2017)
originalEEG = EEG;
channelRejectEEG = EEG;
EEG = clean_rawdata(EEG, 5, -1, 0.85, 4, 20, 0.25);

% If there are channels marked for deletion:
if isfield(EEG.etc, ’clean_channel_mask’)

    % Do not delete the Audio and ECG:
    EEG.etc.clean_channel_mask(64:65) = 1;

    % Manually remove the channels determined by clean_rawdata
    removeChans = {originalEEG.chanlocs(EEG.etc.clean_channel_mask==0).labels};
    channelRejectEEG = pop_select( channelRejectEEG ,’nochannel’, removeChans);

end

% Re-run clean_rawdata just for the ASR
EEG = clean_rawdata(channelRejectEEG, -1, -1, -1, -1, 20, 0.25);

% Interpolate all the removed channels.
EEG = pop_interp(EEG, originalEEG.chanlocs, ’spherical’);

% Add the reference channel back in (We use the EasyCap Standard 64Ch)
EEG=pop_chanedit(EEG, ’append’,63,’changefield’,{64 ’labels’ ’FCz’}, ...
    ’lookup’,[EEGLABroot ’/plugins/dipfit2.3/standard_BESA/standard-10-5-cap385.elp’],...
    ’setref’,{’64’ ’FCz’});

% Re-reference to Common-Average
EEG = pop_reref( EEG, [],’refloc’,struct(’labels’,{’FCz’},’type’,{’’},’theta’,{0}, ...
    ’radius’,{0.12662},’X’,{32.9279},’Y’,{0},’Z’,{78.363},’sph_theta’,{0},...
    ’sph_phi’,{67.208},’sph_radius’,{85},’urchan’,{64},’ref’,{’FCz’},’datachan’,{0}));
```

Listing E.2: The code we used for independent component analysis and dipole localization.

```
function EEG = runICAandCalculateDipoles(EEG, dataDir, rerun)

% Resample to 125 Hz
EEG = pop_resample( EEG, 125);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% COMPONENTS / DIPOLES %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Compute ICA (using AMICA algorithm)
% Following Makoto’s advice: https://sccn.ucsd.edu/wiki/Makoto%27s_useful_EEGLAB_code#Example_of_batch_code_to_preprocess_multiple_subjects_.2801.2F27.2F2017_updated.29

% 1) Compute rank of data (might be rank deficient due to interpolation).
if isfield(EEG.etc, ’clean_channel_mask’)
    dataRank = min([rank(double(EEG.data(:,:,1))) sum(EEG.etc.clean_channel_mask)]);
else
    dataRank = rank(double(EEG.data(:,:,1)));
end

```

```matlab
% 2) Run amica (NOTE: Absolutely NO SPACES in the out file path)
outDir = [EEGLABroot '\amicaout'];
runamica15(EEG.data, 'num_chans', EEG.nbchan,'outdir', outDir,'pcakeep', dataRank, 'num_models', 1,'do_reject', 1, 'numrej', 15, 'rejsig', 3, 'rejint', 1);
EEG.etc.amica  = loadmodout15([outDir]);
EEG.etc.amica.S = EEG.etc.amica.S(1:EEG.etc.amica.num_pcs, :);
EEG.icaweights = EEG.etc.amica.W;
EEG.icasphere  = EEG.etc.amica.S;
EEG = eeg_checkset(EEG, 'ica');

% Now run dipfit (Makoto specifies three cases for the
% coordinateTransformParameters. I think we are case 1, in which case, you
% use the DIPFIT menu to find "Head Model and Settings"
coordinateTransformParameters = [0.83215 -15.6287 2.4114 0.081214 0.00093739 -1.5732 1.1742 1.0601 1.1485];
templateChannelFilePath = [EEGLABroot 'plugins/dipfit2.3/standard_BEM/elec/standard_1005.elc'];
hdmFilePath             = [EEGLABroot 'plugins/dipfit2.3/standard_BEM/standard_vol.mat'];
EEG = pop_dipfit_settings( EEG, 'hdmfile', hdmFilePath, 'coordformat', 'MNI',...
        'mrifile', [EEGLABroot 'plugins/dipfit2.3/standard_BEM/standard_mri.mat'],...
        'chanfile', templateChannelFilePath, ...
        'coord_transform', coordinateTransformParameters,...
        'chansel', 1:EEG.nbchan);

EEG = pop_multifit(EEG, 1:EEG.nbchan,'threshold', 100, 'dipplot','off','plotopt',{'normlen' 'on'});

% Fit Two Dipoles:
EEG = fitTwoDipoles(EEG, 'LRR', 35);

saveSetToDisk(EEG, dataDir, [participantID '_ICA.set']);
```

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