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Interactions between felt emotion and musical change points in live music performance

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Abstract

This thesis in music cognition focuses on investigations of the felt emotions that arise through a listener's response to musical change. The research conducted aims to connect felt emotional response to tension and pleasure in musical signatures, with a focus on qualitative categorization of participant responses.

Participants indicated their felt emotional responses to three recorded pieces of music previously performed for them in a live setting. The focus of the research is on felt emotion, which is relatively unexplored compared to perceived emotion. Participants annotated their overall emotion (in valence-arousal dimensions) and tension through the music. They also annotated where they felt transition points and sudden changes to the overall emotional quality of the piece occurred.

Interactions between felt emotions and musical features, including loudness, tempo, and harmonic and melodic tension, were defined over the length of the performance in both a pedagogical examination and quantitative analysis with the use of music information retrieval software. The conclusions of this study will provide a basis for future music cognition study, especially in medical research of electrophysiological effects of mental stress on the heart and brain.

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1 — Introduction

This thesis focuses on the analysis and categorization of relationships between felt emotional response and specific elements within a piece of music and its live performance. The patients participating in this study will self-annotate both their feeling of tension and emotion, as well as where they felt transitions and sudden change points occurred in the music overall. The primary dimensions of emotion, valence (positive vs. negative feelings) and arousal (energy and liveliness in feelings), are measured both as independent values and against each other to determine the qualitative feeling that lies at their intersection in emotional space (See Section 2.1.)

These aspects of emotion are highly present in music composition and can be both quantified and qualified. For instance, arousal is found to be parallel with the amplitude of the audio signal and relative loudness of the piece overall. Valence is highly linked to musical modes of major and minor, which have well known associations to feeling "happy" or "sad" sounding, respectively, in music across genres. These elements of tonality, loudness, tempo, and tension can be measured with mathematical models, allowing parameters of composition to be quantified and examined against an emotional response.

In this study, annotations were observed against changes in four categories: *(1)* loudness and music dynamic changes, *(2)* tempo and rubato, which is the expressiveness of the performer in subtle tempo changes, *(3)* harmonic structure, and *(4)* melodic structure. These characteristics were examined in quantitative computational analysis and qualitative analysis from a pedagogical music theory standpoint.

1.1 Features of Interest

The study differs from others in the field of music cognition in addressing three relatively unexplored features of the listener's interaction: *(1)* felt emotion, rather than perceived emotion, *(2)* listener-annotated transitions and sudden change points, and *(3)* music in a live setting, rather than a solely recorded presentation.

Felt emotion refers to the listener's individual emotional reaction to the music; in contrast, perceived emotion refers to the perceived emotional quality of the musical piece in a general sense. Felt emotion is often similar to the perceived musical quality, but these two measurements of emotion do not always align due to the emotional ambiguity of expressions within music [1]. This study relies on individual felt responses; the conclusions will examine each participant's interpretation individually and describe what specific musical signatures caused reactions for that participant. Then, these individual interactions will be compared with what was felt across the test group and whether or not the same felt emotion occurred between the participants at each point (See Figure 1.1).

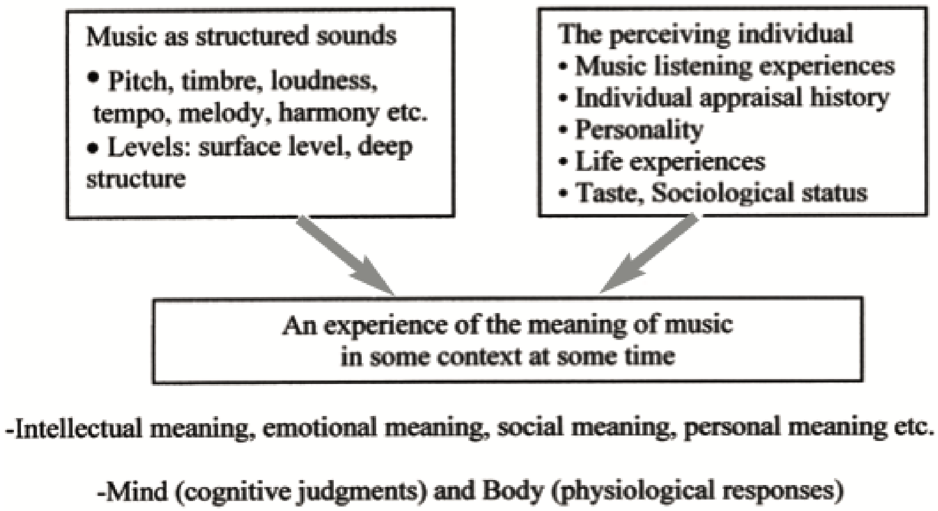


Figure 1.1: A visual depiction of the music experience [1]: Meaning in music is derived from musical structure and the experience of the individual, and depends highly on the context in which the listening took place.

In addition, the inclusion of live musical performance in the study also addresses the heightened response of emotional sharing in an audience setting. Studies in communication ethnography and participation in performance settings indicate that experiencing live performance with others can impact and heighten the emotions of the individual. This is found in instances such as collaborative emotional reactions during stage performances and comedy shows (such as laughing or crying at key points in the performance), and an individual displaying a facial reaction, like smiling, after being told that their friend was experiencing the same activity in the room next door [9, 10, 11]. These studies center around the idea of mutual monitoring, as suggested by Goffman, which outlines the idea that the individual's behavior changes in response to the observed behavior of others in the same setting [12]. The setting of a live piano performance in a church space also gives emotional context to the group of listeners by further assembling in a semantic space [13].

1.2 Thesis Outline

My work on this thesis includes the following components:

- Summary of related studies in music cognition and emotion perception
- Description and explanation of the software developed specifically for conducting this study and the annotation procedure used
- Qualitative analysis of the three pieces performed during the study
- Explanation of the methods and procedures used in the study
- Explanation of software used to measure and quantify musical elements
- Explanation of the data analysis
- Discussion and conclusions from the study

Each of these components is presented in detail through the remainder of this paper. Musical emotion can impact the body in physiological response; this is a growing field of study in medicine, where music is used as a non-invasive stimulus for measuring changes in heart and brain activity. The information gathered from this thesis is part of a larger music-heart-brain study, *Cardiac Response to Live Music Performance*, with the Centre for Digital Music at Queen Mary, University of London (QMUL), Cardiology at University College London (UCL), and cardiologists from the Barts Heart Centre. The felt emotion annotation data gathered for this thesis was collected in tandem with heart data to detect changes in intervals of the heart rhythm during the performance. During the initial live performance, the patient's surface ECG and intra-cardiac readings (gathered through the patient's pacemakers) were measured. The aim of this larger study is to determine the effect of live music performance on electrocardiac activity, with focus on moments of musical change and transition.

2 — Understanding Emotion in Music

Much research has been done to relate emotion to expressions in music and describe why these changes in music induce changes in emotion. Musicologists have described emotional properties of compositional elements to compare and contrast composers and musical styles based on the emotional context they create; yet, there is much less research done in the psychological understanding of musical structure on emotion. Music only recently has become a commonly used stimulus for emotional research. As a stimulus, music is a safe, non-invasive way to induce emotion while still examining the impact on an individual. Emotions are a way of telling the body to prepare for physical reaction (reflected in changes to the respiratory, circulatory, and nervous systems); however, music is observed by the listener in a way where the physical reaction is not addressed to the stimulus itself, and so allows the examination of emotion without any adverse impact on the individual [14]. Much of the existing research in music cognition has been done in regards to perceived emotion and tension, and covers a wide range of musical signatures that are also examined in this thesis.

2.1 Representing Valence-Arousal

To understand the findings of research in music cognition, it is critical to understand the how emotions are represented. Emotional data, being very subjective in nature, is often described in a qualitative focus. In order to better quantify emotions, research has been done to propose methods for building a representational space on which emotions fall based on their relations to each other. The Circumplex Model of Affect (See Figure 2.1) was built on a cross-cultural examination of emotion after determining convergence of valence and arousal values for different emotions in a two-dimensional plane [2]. This study was done to determine different cultural influences by asking participants to place emotion in a valence-arousal space, and provides a global "average" of the circular ordering for emotions in these two dimensions [2].

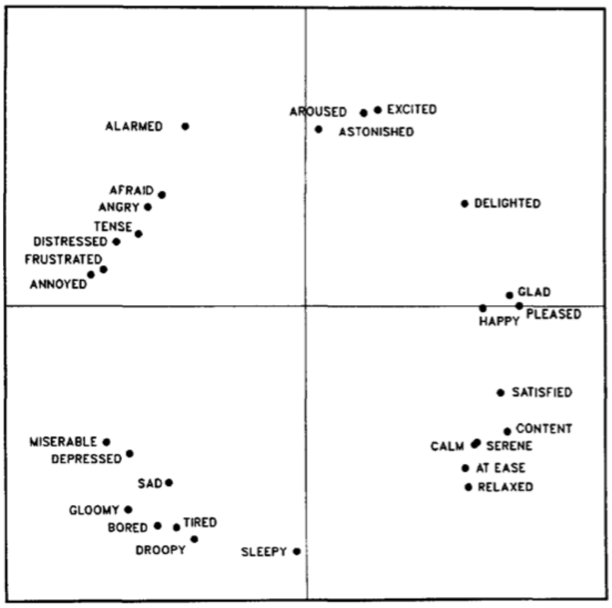


Figure 2.1: The Circumplex Model of Affect [2].

The resulting Circumplex Model of Affect is a Cartesian space and consists of two axes: arousal, the energy level of the emotion being either stressful or calm in the x-axis, and valence, the condition of the emotion being either positive/pleasant or negative/unpleasant in the y-axis. On each axis, zero (0) represents true neutral in that dimension. The emotions were placed on the plane based on the individual participant's judgment of the similarities of feelings to each other. According to Russell *et al.*, participants' comparisons based on the "degree of pleasure and degree of arousal" allow for the reflection of both dimensions in plotting the feelings, clustering similar emotions together and preventing points from gathering at the axes [2].

The measurement of emotion in this two-dimensional axis is common in psychological studies, and valence and arousal are currently the two best explored dimensions of emotional affect. The connection of this non-musical emotion plane to musical emotion was made by Hevner, and now this circle of emotion is widely used in music cognition studies [3]. This study is discussed further in the following Section 2.3.

In this study, participants were asked to indicate their emotion in a valence-arousal space based on the Circumplex Model of Affect, with common emotion-related terms in English being placed around the plane to give the participants the ability to place their felt emotion on a scale compared to other emotions. This is further discussed in Section 4.2.1.

2.2 Representing Tension

Another affect of emotion that is not commonly explored is the idea of tension, or the cyclical feeling of discomfort and release/stability. In music, this can refer to an unresolved chord progression as it moves to back to the tonic, or in sudden changes in loudness and tempo that move the piece away from a feeling of stasis. Tension can be felt often as the music moves away from a main theme into a contrasting section, and then release is felt when the piece returns to the original and familiar progressions and patterns.

Tension, being one-dimensional, is typically represented on a scale ranging from absolute stability and rest to absolute agitation and discomfort. The interface used in a study by Sloboda (discussed in Section 3.2) asked the participants to indicate their tension on a sliding scale from 0 to 100 in this way [15]. The design of the software used in this study is based off the design used by Sloboda and is further covered in Section 4.2.2.

2.3 Relating Music to Emotion

The aforementioned 1936 study by Hevner connects the contextual placement of music emotions to the circular, two-dimensional representation of non-music emotion (as in the Circumplex Model of Affect) [3]. Participants were asked to choose emotional adjectives that best represented several musical selections (See Figure 2.2). Based on these descriptions, it was observed that the music selections inherently had emotional context, and that the emotions follow the same correlations of valence and arousal levels as non-musical emotions [3]. The study affirmed also that modality is closely linked with the ideas of happy and sad, with the major mode being described as "happy, merry, graceful, and playful," and the minor mode being linked with feelings such as "sad, dreamy, and sentimental [3]." Tension and harmonic structure were also linked, with dissonance producing feelings of agitation and consonance producing a feeling of calm [3].

Annotation methodology has been created to address relationships between a participant's responses to musical change. Data from music perception tracking research indicates that, across participants, the mechanisms of perception of valence are consistent (as discussed

Figure 2.2: Hevner's Circle of Adjectives, showing relationships between emotions [3].

in non-musical context by Russell *et al.*[2]) and average models of individual response can be created to reflect changes in this dimension [16]. In the dimension of arousal, however, individual reactions to stress are more variable and any attempt to create a model would differ between each participant [16].

The current belief is that physiological response is more closely related to arousal than valence. In mapping valence and arousal to features of timbre, tempo, musical mode, and density of notes, neural networks have been trained to model emotion judgments [17]. Perceived emotion shows greater relation to valence, while felt emotion shows greater relation to arousal, thus further defining this relationship: felt emotion judgments, which relate more to arousal, correspond more to physiological changes [17]. However, it is difficult to isolate features that reflect each perceived and felt emotion, and it is likely that they greatly impact each other [1, 17].

These major ideas about valence-arousal and tension are further connected to specific compositional elements and musical signatures, which serve as the basis for the relationships explored in this study. These are discussed in the subsequent Chapter 3.

3 Related Studies

3.1 Gomez and Danuser: Valence and Arousal

In felt emotion exploration by Gomez and Danuser [18], connections have been made between features such as tempo, rhythm and articulation, pitch range and melodic structure, consonance and dissonance, and musical mode to emotion. Rhythmically, trends show that felt valence is higher with a faster, brighter tempo. For arousal, increases responded positively with increases in accentuated rhythms. Staccato articulation produced higher values of both positive valence and arousal [18].

Mode has large impact on valence, with minor and major mode corresponding to low and high valence, respectively. These corroborate the ideas that the modes have high association with ideas of "happy"/positive feelings and "sad"/negative feelings [3]. Increased harmonic complexity shows negative valence and high arousal [18], most likely reflecting on discomfort caused by changes in tonality and dissonance.

3.2 Sloboda: Expectancy and Violation in Music Structure

In the 1991 study, Sloboda's empirical findings include that participants claimed "music allowed an intensity of emotional response rarely encountered in everyday life, with beneficial psychological consequences for motivation and self-image [15]." Participants were asked to complete a questionnaire describing physical responses they had recently had to music, detailing the piece and the precise musical event and the reactions they had (with reference to a score, if possible [15]). It was found that listeners were able to apply their own feelings to the non-specific emotional context of the music, where the musical structure allows for the anticipation of release and resolution. Sloboda's study confirmed conclusions of the work of Meyer (1956, cited in Sloboda [15]) and Narmour (1977, cited in

Sloboda [15]), that emotion is closely linked to the expectancy and violation of harmonic structures within a piece.

Sloboda continues this research with Koelsch and Steinbeis in a study measuring physiological reactions to musical structure. Both inter-heartbeat interval (IBI) and electrodermal activity (EDA) were measured while participants listened to Bach chorales and then manipulated versions of the chorales, where the harmonic expectancy had been replaced with a less expected chord sequence; these measures have been related to valence and arousal, respectively (Bradley and Lang, 2001; Bradley, Lang, and Cuthbert, 1993; Lang, Greenwald, Bradley, and Hamm, 1993, cited in Steinbeis, *et al.* [19]). Participants were also asked to indicate continuously their feelings of tension through the piece on a sliding scale and their overall emotionality rating at the end of the piece.

Tension judgments increased with each unexpected harmony, with the most unexpected chord sequences producing the highest tension annotations[15]. The total emotional impact of the piece also increased with the increase in the number of unexpected harmonic events in the music. The study concluded that there is particular sensitivity to the processing of harmonic sequence in musical structure in the Western canon [15].

3.3 Lerdahl and Krumhansl: Harmonic Dissonance and Hierarchy

The feeling of tension has been linked to several musical signatures, namely pitch height of the melody line, note density in the chord structure, and music dynamic changes. Based on the research of Krumhansl [14, 4] and Lerdahl [20, 5], tension is created through a combination of these elements and the surface dissonance of the piece at each event.

Lerdahl has proposed two models of calculating tension: The Qualitative Generative Theory of Tonal Music (GTTM) and the tonal-pitch-space model. GTTM describes degrees of tension and release in a qualitative way, basing the structure of the piece on natural language structure proposed by Chomsky, with sections branching off of the main root as sub-trees based on their difference in tonal and rhythmic structure [21, 22, 23].

The other is the tonal-pitch-space model, which calculates quantitative stability of events in computational modeling as they relate to the tonal hierarchy [22, 20]. The analysis in this study culminates in a representation of Mozart's Piano Sonata in E-flat major, K. 282 as a tree, with the root (the main key center) at the top and branching compositional events and sections of the sonata [4]. As the section branches further from the root of the tree, the tension increases and can be represented quantitatively through the model [20]. Tonal hierarchies are represented in three spaces that define a formula for psychological distance between the branches: *(1)* pitch-class proximity, which classifies notes within a chord structure according to their diatonic or chromatic relationship with each other, *(2)* chord proximity within a key, which classifies chords based on their diatonic proximity to the root, and *(3)* distances between keys and regions, which define larger sections of a piece as they relate to the other regions of the piece [22, 20]. These models are both

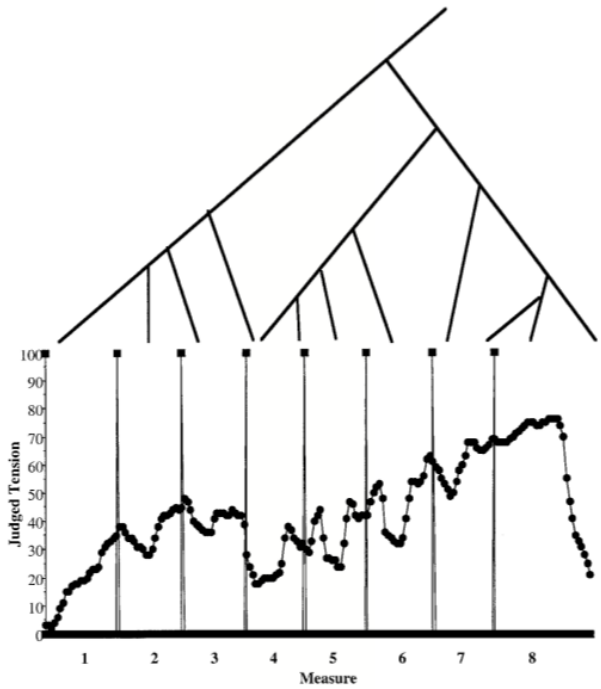


Figure 3.1: The first eight measures of Mozart's Piano Sonata in E-flat major, K. 282, depicted through Lerdahl's (2001, cited in Krumhansl [4]) tree model (top) and listener tension annotations (Krumhansl, bottom [5]), depicting how tension increases with branch distance from the root (Krumhansl, 2000, cited in Krumhansl [4]).

based around the idea that events unlinked to the root of the piece create more tension; when the listener experiences a cognitive dissonance from the tonal root and structural melodic theme of the music, the overall tension of the work increases. Tension can be felt in both the sequential and hierarchal structure of the piece, with listeners hearing one event after another in the composition and also deriving tension from comparison to larger musical sections [20]. In analysis of the same Mozart sonata, Krumhansl derives further, in a model of harmonic hierarchy related to Lerdahl's, that tension is related to the performance expression through the segments of the piece [4]. Participant marking of perceived tension was mapped alongside the tonal-pitch-space tree of Lerdahl's analysis of the piece [20, 24, 4]. Tension increases through the segments due to increases in dynamics, tempo, and note density before tapering off at the end of the section as each of these elements decrease and return to a stasis (See Figure 3.1) – a composed climax and resolution to each section [4, 5].

3.4 Bigand, *et al.*: Melody and Horizontal Motion

Using a participant group of both musicians and non-musicians, Bigand, Parncutt, and Lerdahl affirm in their 1996 study that both Lerdahl's tonal-pitch-space distances [22] and Krumhansl's harmonic heirarchy values model [24] accurately fit the perceived tension calculation of a piece and provide "distinct and complementary" measures of tension [25]. Participants examined a series of short chord sequences while annotating their perception of tension; this analysis confirmed the estimates of the tension models.

They also examined horizontal motion of pitch in the melodic line alongside these models to determine whether cognitive or sensory variables were more involved in feelings of tension. Horizontal motion in the Western canon follows a series of counterpoint rules that dictate which direction the melody should follow to produce the expected resolutions and align with the expected chord structure. Melodic features are the focus of the movement of the piece and can determine the structure of the perceived underlying harmonies [24]. Horizontally, intervals between pitches in different voices (bass, treble, etc.) were examined in relation to the overall perceived tension. Within a voice, a larger melodic interval increased the tension [25] and smaller intervals between a leading tone in the melody and its resolution produced the highest feeling of stability, confirming Bharucha's principal of melodic anchoring (Bharucha, 1984, cited in Bigand, *et al.*, [25]). Close resolutions from leading tones are stronger than those resolving from wider intervals, due to their perceived instability.

3.5 Farbood: Loudness and Timbre

Farbood proposes a global model of quantitative musical tension to predict how listeners will perceive tension. Using three feature descriptions based on models of tonal tension [20], melodic expectation [26], and psychoacoustic loudness [27], Farbood uses linear and logistic regression to fit data from participants' perceived tension of musical excerpts [28, 29]. The study concluded that loudness, tempo, pitch height, and harmonic tension (based on quantification of tension using Lerdahl's model) had significant impact on perceived tension [28, 29, 30]. It was also concluded that harmony was processed over a longer time span than other features, with the participants' memory window duration in tension indication being at least 16.5 seconds longer [30]. In comparison, dynamic changes produced a window duration of 0 seconds, with a near instantaneous tension response [30]. Farbood further explores the role of timbre, which describes sound apart from loudness, pitch, duration, and timing, on tension. Timbre consists of five components: *(1)* inharmonicity (how partials in the sound are offset from the fundamental frequency, causing something to sound in or out of tune), *(2)* roughness (the "beats" heard when waveforms do not align with the dissonance in out-of-tune pitches), *(3)* spectral centroid (which relates to the perceived brightness of a sound), *(4)* spectral deviation (which is used to define the quality of sound produced by different musical instruments), and *(5)* spectral flatness (the similarity of the sound's frequency spectrum to white noise; i.e., the noisiness of the sound). Each of these qualities was examined and inharmonicity, roughness, and spectral flatness were concluded to have impact on perceived tension [31, 32]. This corroborates the conclusion of roughness's impact on tension in the study by Bigand [25]. An increase in any feature produced increase in perceived tension [31]. The brightness of the sound with respect to the spectral centroid was confirmed to show little impact on psychological perception (Schubert, 2004; Bailes and Dean, 2012, cited in Farbood [32]). It thus appears only some components of timbre of have impact on tension; however, it is difficult to achieve isolation because of variations in loudness and pitch [31].

3.6 Musicians vs. Non-Musicians

Each of the features examined relate to distinct cognitive processes and to different parts of the musical hierarchy. Across studies, non-musicians perceived stronger changes in tension alongside changes to melodic relation to the chord structure and pitch height [29], while musicians were more alert to the specific function of individual chords within the harmonic structure and any dissonance they might have [25, 29]. Musicians reacted more to every parameter of the musical structure except for pitch height, where harmony changes were favored in impact to tension [29]. This the only significant difference found between musician and non-musician listeners. Regardless of the listener's music background, this reiterates that expectancies in the melodic and harmonic structures provide the most stability, and tension is caused when the anticipation in the piece is not resolved as expected [15, 5].

4 Data Selection

This study involved a selection of three works in varying styles. Pieces were chosen to include frequent changes to loudness and dynamics, tempo, and harmonic and melodic structure for examination against annotation data. Music was exclusively from the Western canon; with series of expectations that most people (musical or not) are familiar with, this canon is most often the focus of research in music cognition [16].
The three works ultimately chosen were all for solo piano and include:

1. Chopin - *Ballade No. 2, in F Major, Op. 38*
2. *VT before during after* (taken from Holst – *The Planets, Op. 23, Movement 1, Mars, the Bringer of War*)
3. *VT before after UNI* (taken from Chopin - *Ballade No. 2, in F Major, Op. 38*)

The second and third selections are from the *Arrhythmia Suite* by Chew, Krishna, Soberanes, Ybarra, Orini, and Lambiase. This composition uses existing musical material but replaces rhythms with patterns of irregular heartbeats. The compositions were part of the *music, computing, cardiology* project and incorporate patterns of ventricular tachycardia and atrial fibrillation collected from ECG data. Through the music, these irregularities can be felt by those who have not experienced arrhythmia, and the patterns can be examined as rhythmic patterns in relation to music. These pieces were chosen as special interest to see if the use of rhythmic features relating to irregular heartbeats induced interesting change in the heart monitoring that was done alongside this study.

4.1 Descriptions of Pieces

Each piece used in the study is described based on its score with focus on the notable musical signatures that were considered during the program selection. Unique characteristics of the pieces as performed live during the study are further discussed in the examination of data in Chapter 6. The pieces were performed in the order in which they are listed in this paper:

4.1.1 *Chopin - Ballade No. 2, in F Major, Op. 38:*

Ballade No. 2 is composed in 6/8 meter, giving the feel of triplets the whole way through the piece – this is usually associated with a bouncy, lilting feeling to the listener. The piece starts out very softly, quietly introducing the main triplet theme in a calm and slightly repetitive feel. There are a few chords in the structure out of the main expectancy, with a few of the high voice notes falling slightly out of the anticipated chords; as this section goes on, there are more violations of expected chord progression. This initial section quietly fades out before the piano returns dramatically with a *fortissimo* dynamic, causing a large shock factor to the unsuspecting listener. The melodic line rapidly rises and falls in pitch, with the bass taking over at the end of the phrase, resulting in high note density. The treble voice dissipates to a syncopated feeling and then returns to steadily landing on each beat while the bass rolls underneath in chromatic lines. The section fades out before returning to the original triplet theme in a slightly more minor feel. The piece transitions back and forth between this tumultuous section (referred to in this paper as the ”storm” section) and the familiar triplet theme. The piece ends with a harsh, high note density storm section, which becomes more syncopated and violates more harmonic progression as it advances, before returning to the triplets once more in the most minor variation of the theme in the piece.

4.1.2 *Chew, Krishna, Soberanes, Ybarra, Orini, Lambiase - VT before during after (Holst):*

Mars is a well-known piece in the Western canon, with its blocky, spread, dissonant chords, syncopation and near-constant removal from any mode or expected harmonic progression. The rhythms in this arrangement are also more syncopated due to the inclusion of irregular heartbeat rhythms. There are large spaces between the bass and treble voices in the piano constantly through the piece, resulting in feelings of instability; resolutions are less satisfying when they do occur because of the removal from a tonal center. The dynamic range of the piece is very large with many climaxes and few clear sections to the listener. Very few of the phrases make up coherent patterns or are repeated, meaning there are very few points during the length of the piece that feel familiar or can be related back to another musical thought. The piece ends very abruptly with all voices in dissonant unison, preventing any final resolution to the harmonic structure.

4.1.3 *Chew, Krishna, Soberanes, Ybarra, Orini, Lambiase - VT before after UNI (Chopin):*

The arrangement of this piece includes all of the harmonic violations, note density, and loudness as the original scoring described above in Section 4.1.1, with the addition of arrhythmia patterns in the rhythm. These remove the stability of the main theme deriving from the triplet feel and add much rhythmic syncopation, making it hard for the listener to detect a pulse through the piece. There are more harmonically unexpected chords added in arrangement of these main sections, as well. During the contrasting storm sections, slight syncopations catch the listener off guard and interrupt the rolling sensation of the bass line and the chromatic lines in the treble. Sections begin and end without proper warning, compared to the structure of the original piece; however, this arrangement ends pleasantly on a well-resolved tonic in the major, giving the listener a bit of peace after the near constant advancement of unexpected events.

4.2 Annotation Procedure

Participants were asked to indicate in three separate programs their felt valence-arousal, tension, and transition and change points through the duration of the performance. This project included design and implementation of the Valence-Arousal interface, which is detailed in this section.

4.2.1 Valence-Arousal Interface

The emotional plane for valence and arousal mapping was derived from the Circumplex Model of Affect based on the connection to the model of musical emotions by Hevner, as described in Sections 2.1 and 2.3 [3, 2]. A square, two-dimensional axis was created with the same arousal-valence axes. Several versions of the interface where examined amongst 5 students with backgrounds in interface design in the MSc Computer Science and Software Engineering program at QMUL. It was eventually decided to use an interface where emotion-related words were organized around the display to give participants a reference to place their own felt emotions without having to quickly think about the position on the axis (See Figure 4.1). It was prior thought that this may introduce bias by forcing participants to indicate around only the words chosen, but it was ultimately deemed more beneficial to include the labeling so that there was less time delay between a cognitive reaction and movement on the physical interface. The interface using this visual display was designed using the Psychophysics Toolbox Version 3 (PTB-3) extensions, a Matlab toolbox set of functions designed for synchronization of visual and auditory stimuli in psychological and neuroscience research. PTB-3 is composed of Matlab and GNU Octave functions and was chosen because of its ability to provide accurate synchronization and time stamping for participant annotations [33, 34, 35].

The Matlab application first requests a Patient ID number from the user before loading the interface. Using the mouse, the participant can move the cursor (no clicking required, for ease of use) to the desired location on the scaled axis. Using the pixel coordinate location of the cursor, the position is scaled to dimensions of -100 to 100 on each axis, with the axis at 0 being true neutral in each dimension; from left to right, the energy (arousal) increases, and from bottom to top, the positivity of the emotion (valence) increases. The location of the cursor is sampled at a rate of 20 samples per second with time-stamping provided by the PTB-3 function *GetSecs*, which uses the computer's internal clocking [36]; this functionality of PTB-3 is the primary advantage to using the extensions in Matlab.

Annotation data is inserted into a matrix with preallocated size 3x30000 in Matlab, where the x and y position of the cursor (arousal and valence, respectively) and the time-stamp of each event are placed into three columns. This matrix is then saved as a CSV named with the participant's ID number and the time-stamp of the first sample taken, to distinguish the data from other participants and other later trials. The program continuously monitors cursor position and time-stamp at 20 samples per second and appends the values as a row to the data matrix. Because of this continuous monitoring, it was decided by the research team to use an external cue to determine when the audio and participant annotations should begin. This also allows synchronization with the other data streams from other interfaces and audio, as discussed in Section 5.2.

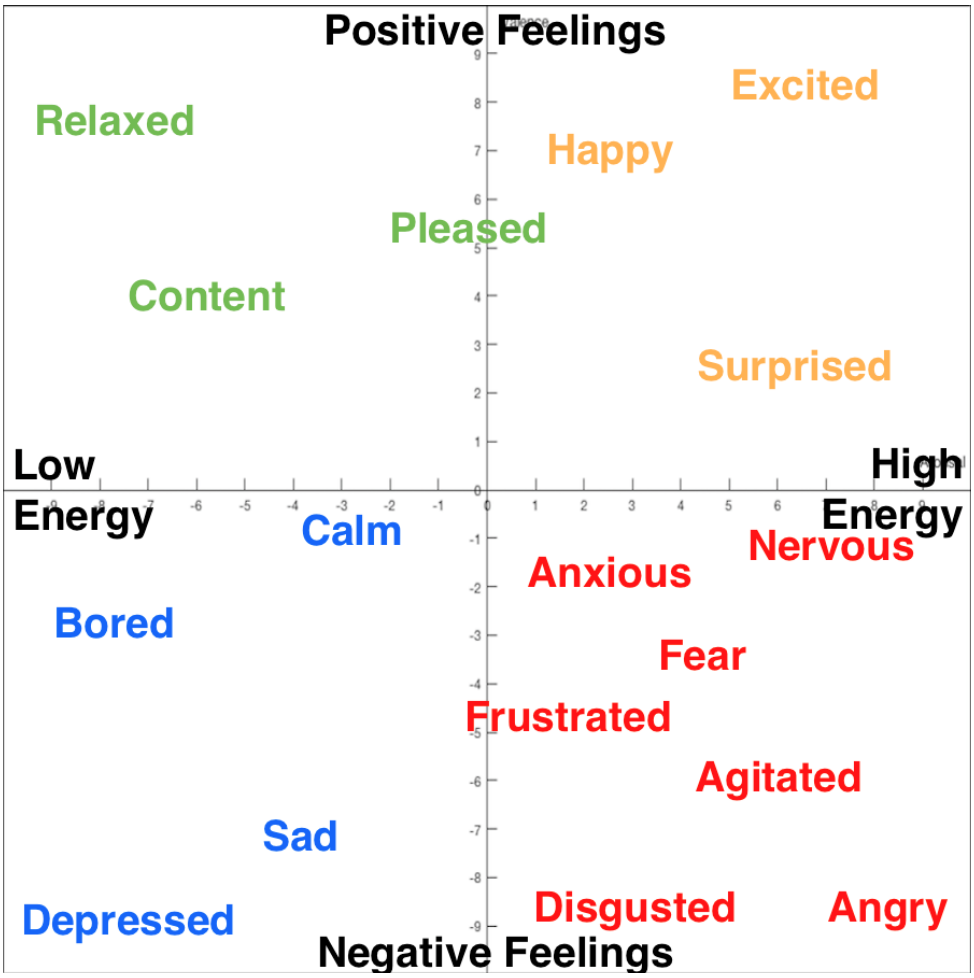


Figure 4.1: The Valence-Arousal interface display.

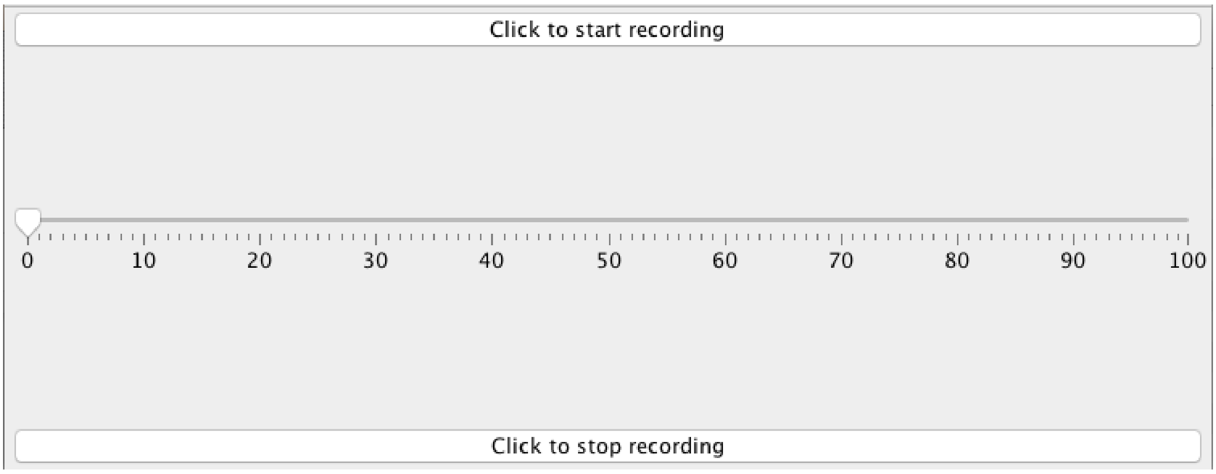


Figure 4.2: The Tension slider interface.

4.2.2 Tension Slider Interface

A moving slider was designed by BSc Computer Science (QMUL) student Shamindra De Zylva for tension annotations. The slider was programmed in Java and works with a click-and-drag function to allow the participant to mark their tension feeling by dragging the cursor to a position or clicking between desired values (See Figure 4.2). The slider is also set on a scale from 0 to 100 [15], with 0 being completely at peace and calm and 100 being the most agitation and discomfort. At the beginning of the recording, a 'Click to Start Recording' button is clicked, which begins the tracking of slider position and time-stamps. The data is not continuous, but records the location and time-stamp when a new position is recorded and saves the data to CSV when the 'Click to Stop Recording' button is clicked.

4.2.3 Transition and Change Point Annotation

The third and final annotation interface used for change points and sudden transitions was done in the program ELAN, a tool typically used for analysis in psycholinguistics [37, 38, 39]. ELAN allows the user to import an audio file (in this case, the recording from the live performance) and for annotations to be made alongside the waveform (See Figure 4.3). While the other two interfaces are participant-controlled, the transition marking in ELAN uses more key commands. The annotation itself also requires participants to reflect more on their feelings of where changes occurred in the piece; in order to make sure that the felt transitions and change points where marked accurately to the participant's intent, student members of the research team annotated on behalf of the participants. The participants were supported by starting and stopping the audio recording so they could hear and confirm their annotations and reflect as long as they needed without worry of continuous tracking or timing.

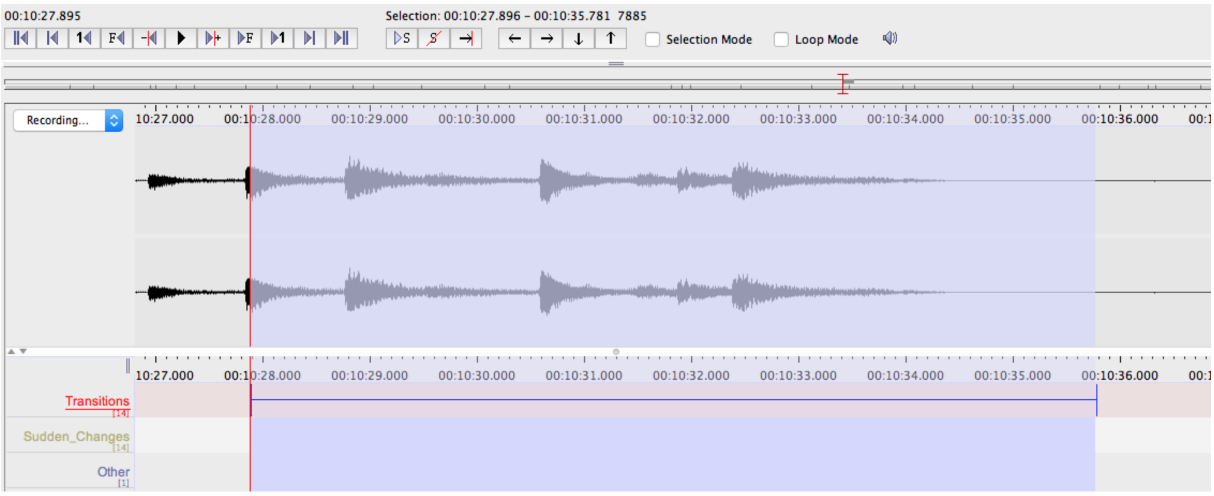


Figure 4.3: The editor window of ELAN with a marked Transition highlighted and displayed against the audio signal.

All systems measured time-stamps to the millisecond (0.001 seconds). Before the testing, the software was installed and reviewed by members and organizers of the research team, and functionality was confirmed for participant use. A one-hour session was conducted to allow for members of the research team to familiarize themselves with operating the interfaces, ensuring they were able to support participants and troubleshoot, if needed.

5 — Method

The testing for *Cardiac Response to Live Music Performance* was organized by Professors Elaine Chew, (QMUL – Digital Media at the School of Electronic Engineering and Computer Science) and Pier Lambiase, (UCL – Cardiology, and Barts Heart Centre), and Peter Taggart, Emeritus Professor of Cardiac Electrophysiology at UCL. The study also involved the help of MSc and PhD students from QMUL and UCL, a clinical trial coordinator, a team of research nurses, 4 consultant cardiologists, and 2 device programmers (responsible for the programming of the patient's pacemakers).

Patients were selected for participation in the trial for the larger cardiac study being conducted alongside the emotion analysis. Following ethics approval (the Patient Information Sheet and the Informed Consent Form in the PIS-ICF document are included in Appendix A), participants were recruited on a volunteer basis by the clinical trial coordinator and research nurses in Professor Lambiase's team. The participants were heart patients who already had biventricular pacemakers/intracardiac devices (ICDs) by the device company, Abbot, who helped with the heart data decryption and normalization. A total of three participants were observed in the study for this thesis.

5.1 Gold-MSI Questionnaire

Participants arrived at the test location, St. Bartholomew-the-Great Church in West Smithfield, London, and were given a full Goldsmiths Musical Sophistication Index (Gold-MSI) questionnaire to complete (See Figure 5.1 and Appendix B). The Gold-MSI is designed to gather data about an individual's ability to engage in music and their amount of formal musical training, listening skills, and ability to describe musical emotional qualities [6, 7]. Participants are asked to rate their agreement with statements about their musical abilities and training and provide demographic background.

Please circle the most appropriate category:	1 Completely Disagree	2 Strongly Disagree	3 Disagree	4 Neither Agree nor Disagree	5 Agree	6 Strongly Agree	7 Completely Agree
1. I spend a lot of my free time doing music-related activities.	1	2	3	4	5	6	7
2. I sometimes choose music that can trigger shivers down my spine.	1	2	3	4	5	6	7
3. I enjoy writing about music, for example on blogs and forums.	1	2	3	4	5	6	7
4. If somebody starts singing a song I don't know, I can usually join in.	1	2	3	4	5	6	7
5. I am able to judge whether someone is a good singer or not.	1	2	3	4	5	6	7
6. I usually know when I'm hearing a song for the first time.	1	2	3	4	5	6	7
7. I can sing or play music from memory.	1	2	3	4	5	6	7
8. I'm intrigued by musical styles I'm not familiar with and want to find out more.	1	2	3	4	5	6	7
9. Pieces of music rarely evoke emotions for me.	1	2	3	4	5	6	7
10. I am able to hit the right notes when I sing along with a recording.	1	2	3	4	5	6	7

Figure 5.1: The first 10 questions of the Gold-MSI questionnaire with the rating scale for each statement [6, 7].

5.2 Testing Procedure

After the completion of the questionnaire, the three participants had their pacemakers reprogrammed to eliminate a variable heart rate in the data, and allowing for a focus on the intervals of the heartbeat. Audio recording began, followed by the reprogramming. An initial clap by Professor Lambiase in the audio indicated to the technicians to set the new device pacing, allowing for later synchronization between the electrical heart measurements, audio, and annotations of emotion. A period of 10 minutes was given to set the pacing of the heart and allow the participants time to adjust to the sensation of a different pacing, to ensure that they felt well enough to continue to study. Participants were monitored by 12-lead ECG and through data collection from their pacemakers.

After the 10-minute period, PhD student James Weaver (QMUL, Centre for Digital Music) provided an initial loud indication clap for audio synchronization, followed by 3 additional claps. Participants listened to the three-piece live music program, performed by Professor Elaine Chew on piano, while readings were taken from their hearts. Following the performance, the entire audio recording was saved as a WAV file and condensed by

James Weaver into an additional shortened audio file including his indication and three additional claps without the 10-minute resting period; during this time, the participants' pacemakers were returned to their original settings and they were given another adjustment period.

Participants were then brought into another room for the annotation stage where they reviewed the short recording of the performance. They were instructed to reflect on and indicate their feelings through the piece during the live performance. The basic concepts of valence-arousal, tension, and transitions and sudden changes were explained to the group of participants to ensure they had a base understanding of the requested annotations. Each participant used headphones to listen to the recording and operated the software with a USB mouse connected to a MacBook laptop for all three of the annotation programs. Students from the research team helped participants understand and practice using the annotation software, with a small demo instruction given of the Valence-Arousal and Tension interfaces. Participants were allowed to ask questions and the testing proceeded once all participants felt they understood how to correctly annotate the felt emotions.

For synchronization, the participants were informed that they would hear again the strong indication clap, followed by the three additional claps, and that they should begin marking their felt emotion as soon as they heard the third and final additional clap. There is a period of silence between the final clap and the beginning of the first piece, during which the participants also marked annotations as a way to see their feelings of anticipation before the onset of the music. Participants listened to the recording three times, once for each annotation method – felt valence-arousal, tension, and sensed transitions/sudden changes, assisted by students in the test group if needed.

5.3 Quantitative Music Analysis

In addition to the annotation data streams, data was gathered from the music itself, through scores and the recording of the live performance. Several different methods and software were used to piece together a quantitative analysis of the musical performance.

As outlined in Chapter 1, four features were examined: *(1)* loudness and music dynamic changes, *(2)* tempo and rubato, *(3)* harmonic structure, and *(4)* melodic structure. Analyses were made in the software Sonic Visualiser (SV), an application developed by the Centre for Digital Music at QMUL. SV allows for layers of different music elements to be plotted as data points and line graphs against an audio signal [40, 41].

5.3.1 Loudness and Dynamic Changes

Changes in the dynamics of a piece coincide with crucial parts of the composition and composers often use loudness changes to focus the listener's attention on these details. Loudness was calculated from the recorded audio of the performance using the *ma_sone* function from Matlab extension MA Toolbox [42, 43, 44]. The loudness program [44, 45] analyzes the WAV file's pulse-code modulation (PCM) representation of the audio signal using different auditory models to estimate the sensation of loudness per frequency band at the time of the recording (See Figure 5.2). Models used in *ma_sone* include the outer-ear model, critical-band rate scale (Bark-scale), spectral masking, and Sone to compute a sonogram for a PCM signal [42]. These models represent critical bands of hearing of audible frequencies by the human ear and are based off psychoacoustic scales that estimate loudness based not on the amplitude of the audio signal itself, but on how a listener would perceive the loudness to be. Loudness is a subjective measure and differs from amplitude because the shape of the human ear resonates more with certain frequencies (whether that be the pitch of a note or in the timbre of a sound with partials at these frequencies), causing some sounds to seem louder than others, even those with the same amplitude. It is important to distinguish between loudness and amplitude in measuring audio signals because of this natural bias to a listener.

Using the Pruned Exact Linear Time (PELT) and CROPS from the "R" package *changepoint* [46], change points in the dynamics of a piece can be identified in time (See Figure 5.2) as peaks in the loudness measurement compared to surrounding features in the audio signal [43, 44, 45]. Change points in music are found to be responses to different types of boundaries in the score, most typically composer-specified dynamic markings,

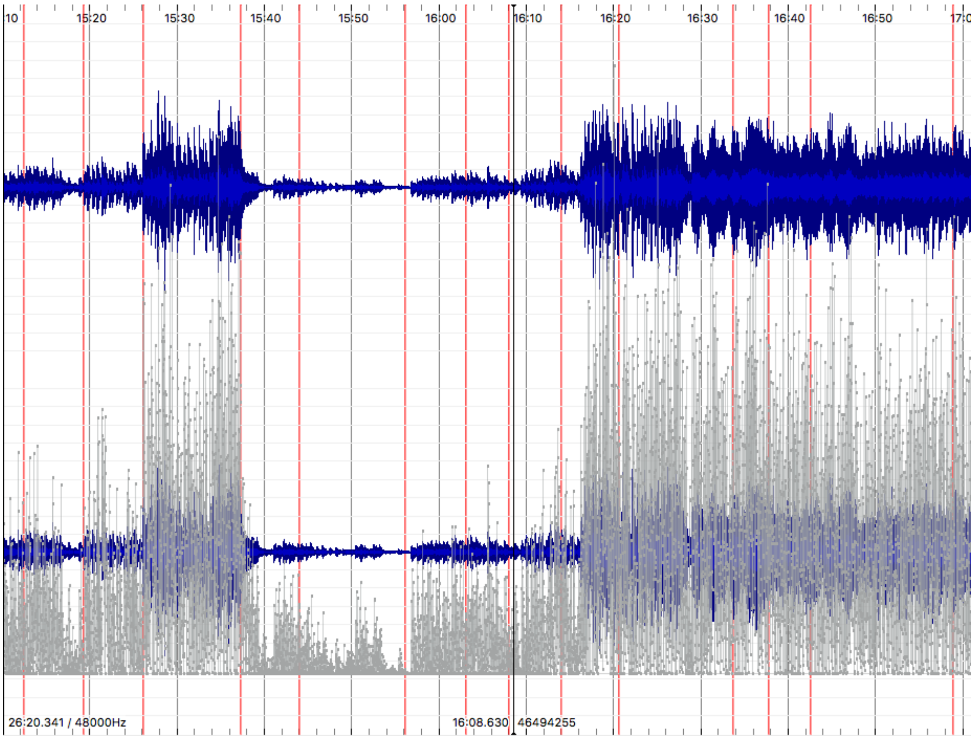


Figure 5.2: Sonic Visualiser window displaying time instants of change points (red) based on calculated loudness Sone values (grey) against the audio signal (blue).

accents, and tempo and expression markings that give the performer instruction for how sections should be played [45]. Other boundaries in the motif of the piece and individual expression will also be reflected in loudness as the performer highlights the expression to the listener [45].

5.3.2 Tempo and Rubato

Individual beats in each piece were marked by hand in SV as time instants to track the pacing of the performance and internally in each piece. In *Ballade No. 2*, the eighth note pulse was marked as played, while the "beats" marked in *VT before during after (Holst)* and *VT before after UNI (Chopin)* followed the underlying irregular heartbeats. After marking each individual beat (See Figure 5.3), a Time Values Layer using these beats as data points was added in SV using a value calculation of "Tempo (BPM) based on duration since previous item." This allows for the calculation of tempo in BPM (beats per minute) in detail by measuring the spacing of each beat compared to the position of the previous

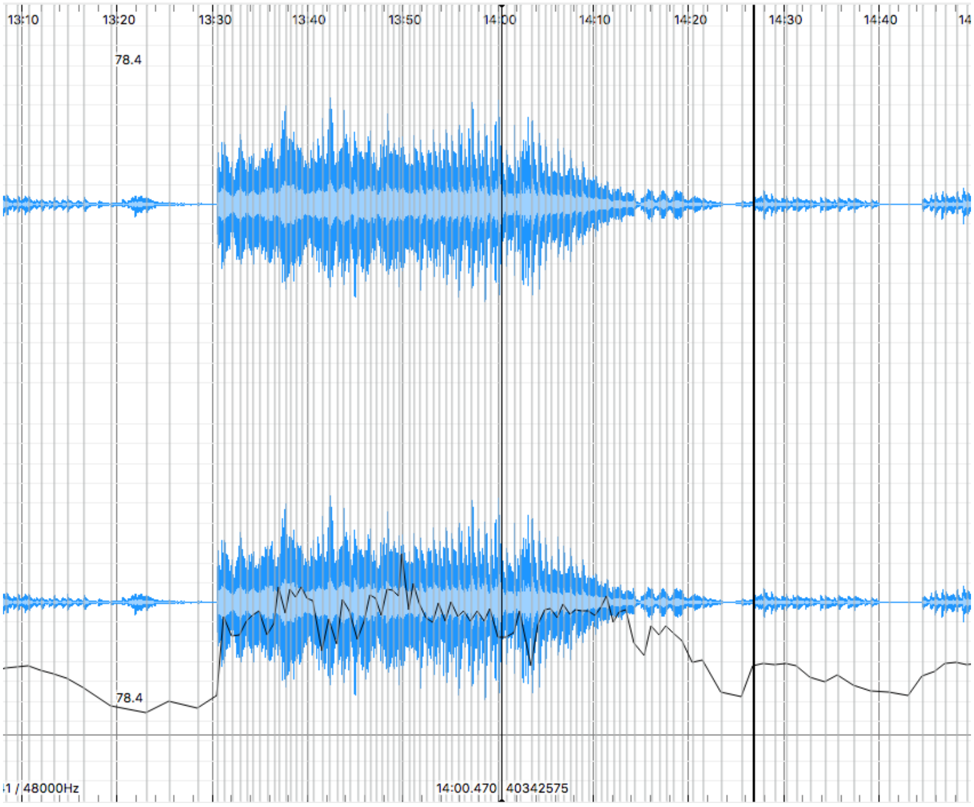


Figure 5.3: A Sonic Visualiser window depicting the mapped beats as Time Instants (grey) and rubato as a measure of distance since previous instant (black), displayed against the audio signal.

beat. This measurement shows where the performer slightly lengthened or quickened the pulse, or where a tempo change occurred either suddenly or over time (See Figure 5.3). These small liberties taken with the tempo are found in both composed markings and in the performer's discretionary choice to add expression to a phrase, highlight a change in the motif, or savor a tension or resolution in slightly lengthened time.

Tempo was also calculated through the use of SV VAMP plugin Tempograms (See Figure 5.4), which calculates cyclic tempograms as "tempo-based counterparts of harmony-based chromagrams," which were proposed as a strategy for segmenting audio signals to detect sections within a musical piece [47]. A change in tempo shifts the cycling of the calculated tempogram, which is done by mapping T to a time parameter measured in seconds and a tempo parameter measured in BPM, where T (t, τ) indicates to which extent a pulse of tempo τ is present at time t [47]. This allows calculation of the tempo characteristics without the influence of the pulse level, as done in the case of the manual beat mapping described above.

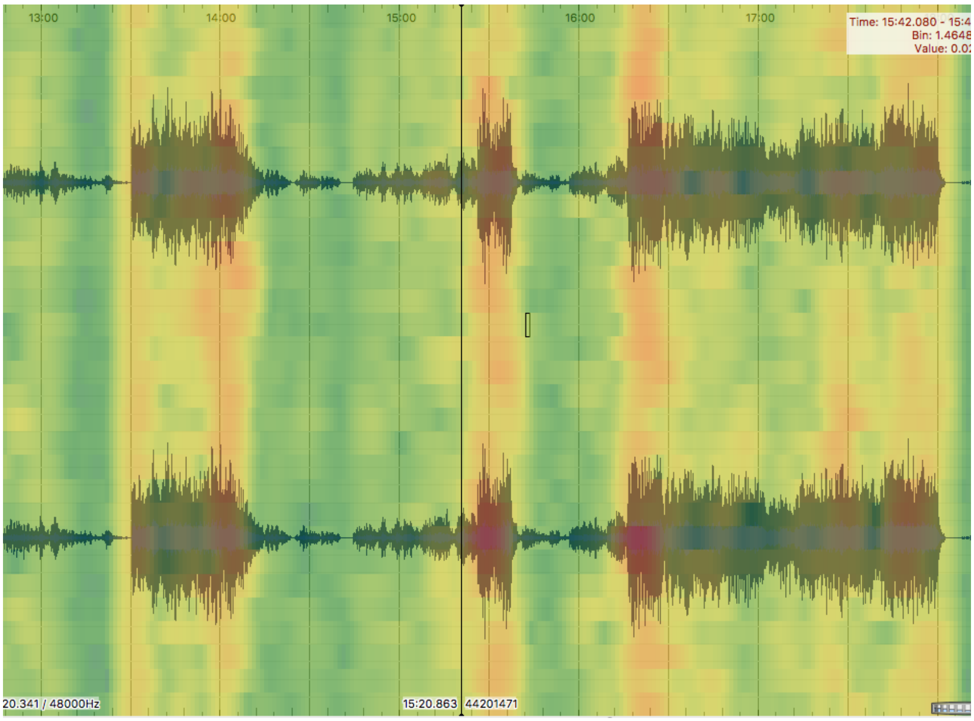


Figure 5.4: A Color 3D Plot of tempo values calculated by Cyclic Tempograms displayed in Sonic Visualiser against the audio waveform.

5.3.3 Harmonic and Melodic Structure

For this study, analysis of the harmonic and melodic structure comes through the use of the MorpheuS Tension Visualiser, a program that calculates tonal tension ribbons based on the score of a piece [8]. MorpheuS uses pitch information from a MusicXML score file to calculate tension following models of spatial structure and hierarchy in music [8]. This aligns with models such as those proposed by Krumhansl, Lerdahl, and Farbood (as described in Sections 3.3 and 3.5) where distance is measured along a spiral array to relate pitch classes, chords, and keys (See Figure 5.5); the helix model allows for close tonal relationships between pitches to be pictured as close in proximity within the 3D space [48, 8, 49].

The piece is divided into equal-length segments (i.e., the beat measurement, the default is one 1/8th note) where points are then mapped to "clouds" of points within the helix with a center of effect - an aggregate tonal center of its components [8]. Tension is calculated through measurements of *(1)* cloud diameter, the dispersion of the grouping within the tonal space, *(2)* cloud momentum, movement between two consecutive clouds,

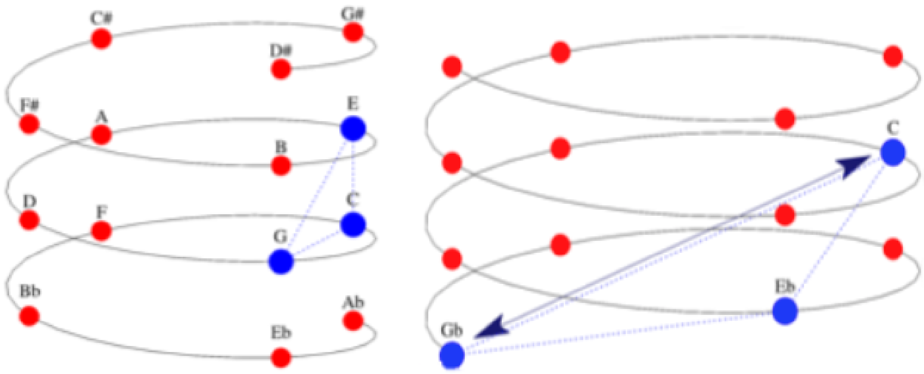


Figure 5.5: The spiral representation of tonal relationships as used in the MorpheuS Tension Visualiser. A C major triad is depicted (left) in comparison to the same triad with a diminished third and fifth (right); the distance between the notes reflects the dissonance of the diminished triad compared to the stability of the major triad [8].

and *(3)* tensile strain, the distance between the center of effect and the position of the key in the helix [8, 49]. Listeners have been shown to identify these points as being transitional spaces within the structure of a piece, particularly in boundaries between areas of high tension and the return of a common motif [50].

For each piece, the tension was calculated in the three areas (See Figures 5.6, 5.7, 5.8). It is important to note that the software utilizes data from MusicXML representation of the score, and not the audio of an individual performance. Small pitch mistakes or other deviations from the score in the live rendition may have impact on the analysis of the piece; however, the performance in this study is highly accurate to the composition as written. Any deviations are too minor to be considered in this case. It should also be considered that MorpheuS, which was developed for small phrase analysis, currently does not account for divisions per quarter note and errors may occur due to changing meter (an occurrence in the *Arryhthmia Suite* pieces), which impacts the division of the piece into even slices, and thus point assignment into clouds [48].

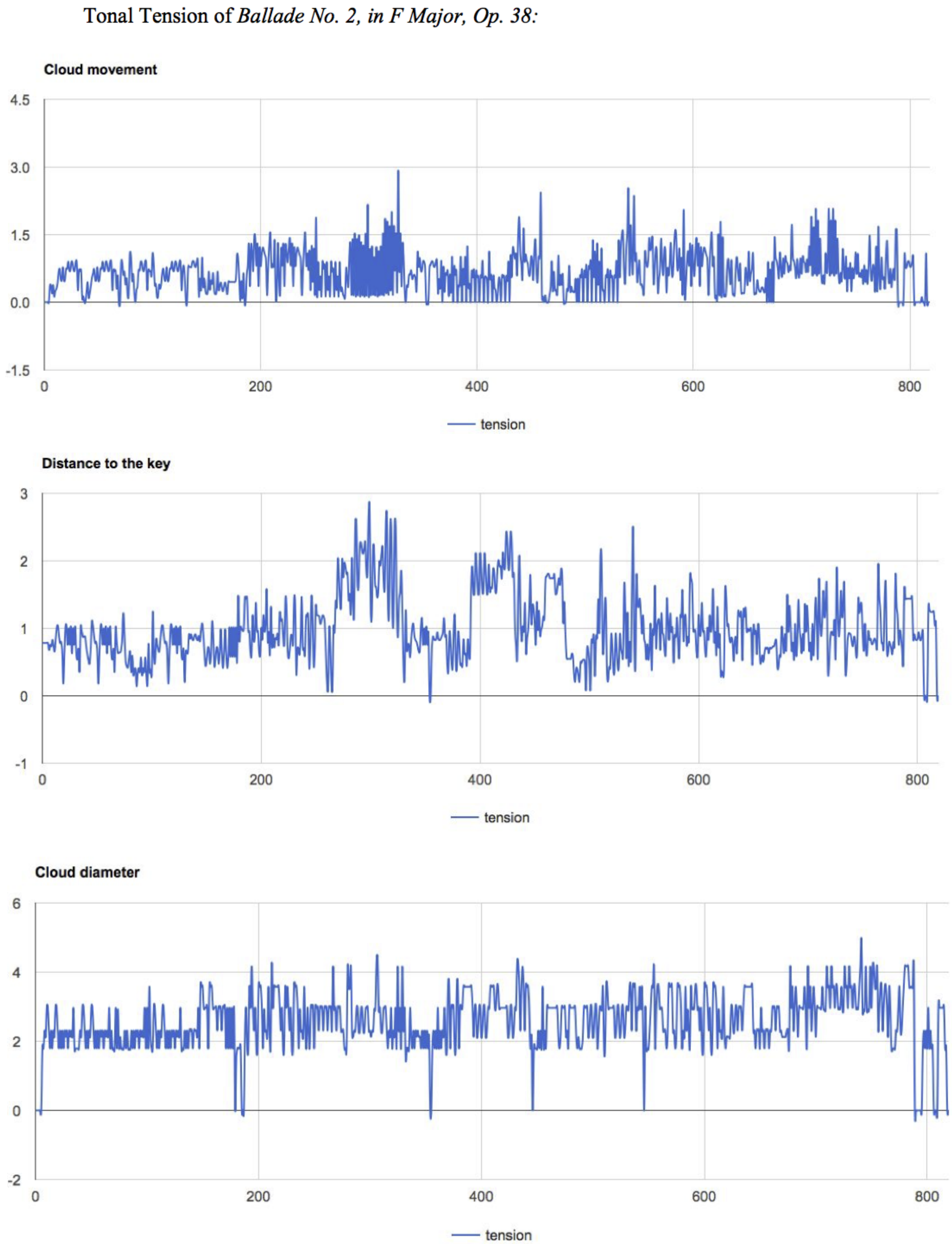


Figure 5.6: Tension over time in *Ballade No. 2, in F Major, Op. 38* (Chopin) calculated by MorpheuS.

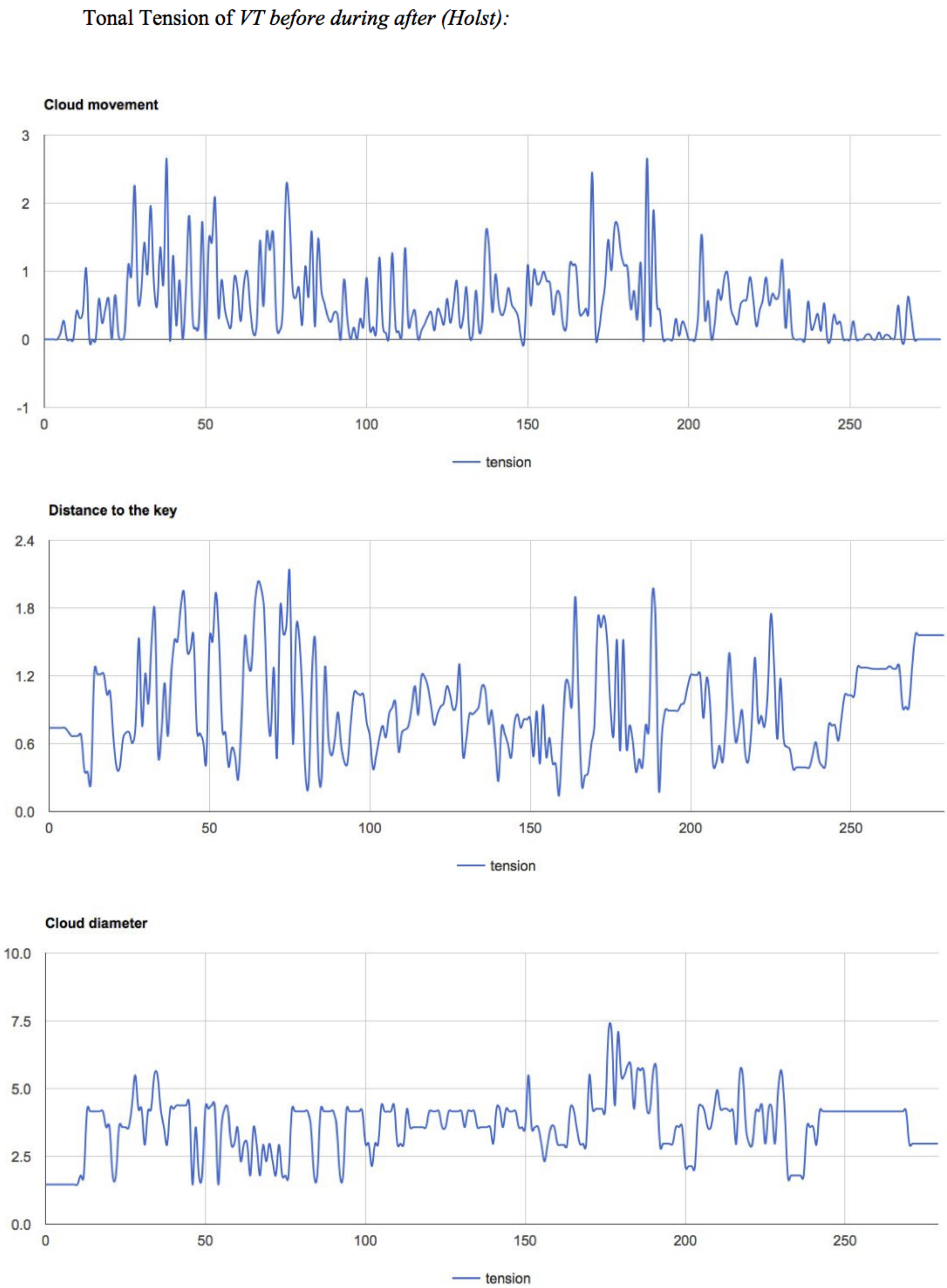


Figure 5.7: Tension over time in *VT before during after* (Chew *et al.*) calculated by MorpheuS

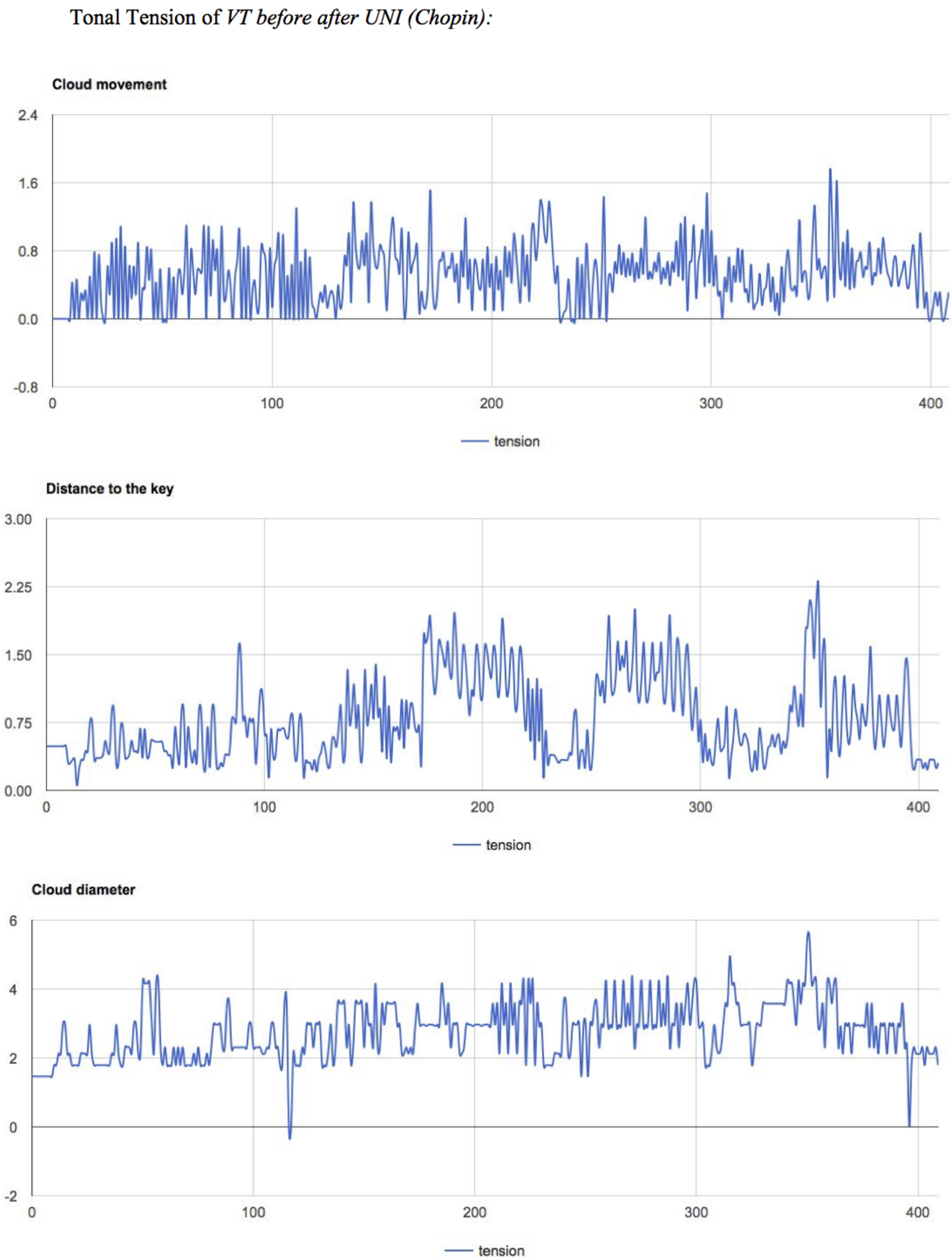


Figure 5.8: Tension over time in *VT before after UNI* (Chew *et al.*) calculated by MorpheuS

6 — Analysis

This section covers the analysis of data collected during the research. First, a general qualitative overview of the results from the Gold-MSI is included, to determine the musical background of each participant. Then, in each annotation software, individual participant‘s markings are discussed and summarized. Again, because of the subjective nature of music-emotion interaction, data is analyzed both qualitatively and quantitatively. The main quantitative analysis focuses around the following points: *(1)* how many changes in valence-arousal and tension did each participant feel through the performance, and how many transitions and changes were marked; *(2)* of those, how many coincided with a major musical event, *(3)* what was that event, and *(4)* how many annotation changes correlated with each element examined. Qualitative analysis will focus on relating these data streams and attempt to describe how the participant was feeling at the change point, why some musical events were more noticed, and what types of change points in the music cause the largest reactions.

6.1 Gold-MSI Results

In order to determine how much musical experience each participant had, a Gold-MSI was completed. Of the three participants, 2 were male and one was female. Participants 1 and 2 had a general knowledge of music as a hobby and Participant 3 had extensive musical knowledge as a harpsichordist. All participants were over the age of 50 and currently reside in the UK; Participants 1 and 2 had grown up in England and were over the age of 60, while Participant 3 had grown up in Japan and later moved to the UK. All participants had at least an undergraduate degree or equivalent professional qualification (See Figure 6.1).

The Gold-MSI questionnaire only includes Western musical genres as options for the question "What is the musical genre you mainly listen to;" each participant involved selected one of the options available – jazz, rock/pop, and classical, thus covering a range

Question	P1	P2	P3
32	0	0	10 or more
33	0	0	5 or more
34	4-6	2	11 or more
35	0	0	7 or more
36	0	0	10 or more
37	0	0	2
38	15-30 min	15-30 min	2-3 hrs
39	N/A	N/A	Harpsichord
Occupation	Retired	Retired	Self-employed
Genre	Jazz	Rock/Pop	Classical
Education	Undergraduate degree or professional qualification	Undergraduate degree or professional qualification	Postgraduate
Highest Degree Expected to	N/A	N/A	N/A
Age	63	70	55
Gender	M	M	F
Nationality	British	British	Japanese
Country of Youth	England	England	Japan
Country of Current Residency	Britain	England	UK

Figure 6.1: Results of the demographics and musical training section of the Gold-MSI with information for Participants (P) 1, 2, and 3.

of Western styles in the participant pool. All participants also indicated at least moderate exposure to Western music and enjoyment from listening to it. All participants were active in attending musical events in the last 12 months (Question 34), with Participant 1 indicating 4-6 events, Participant 2 indicating 2 events, and Participant 3 indicating 11 or more events (See Figure 6.1).

All participants responded with feelings of strong emotional connection to music (See Figure 6.2). Each participant expressed disagreement to the statement "Pieces of music rarely evoke emotions for me (Question 9)," with an average response being 1.33 out of 7 - between "Completely Disagree" and "Strongly Disagree." All participants also responded positively to the statement "I often pick certain music to motivate or excite me (Question 16)," with the average response being a 6.0, and in regard to their ability to speak about their emotional response to music in the statement "I am able to talk about the emotions that a piece of music evokes for me (Question 20)," with the average response of 5.67 – "Strongly Agree" and "Agree," respectively. The statement "Music can evoke my memories of past people and places," also received strong positive response, averaging 6.67 – between "Strongly Agree" and "Completely Agree."

While all participant felt very strongly about the emotional qualities of music and their

Question	Patient 1	Patient 2	Patient 3	Average
1	4	3	5	4.00
2	6	4	2	4.00
3	1	2	3	2.00
4	4	1	5	3.33
5	4	3	6	4.33
6	5	3	5	4.33
7	1	1	6	2.67
8	5	3	2	3.33
9	2	1	1	1.33
10	1	2	7	3.33
11	7	5	7	6.33
12	4	5	7	5.33
13	3	3	2	2.67
14	7	7	2	5.33
15	2	4	7	4.33
16	5	6	7	6.00
17	3	7	2	4.00
18	5	5	7	5.67
19	3	3	5	3.67
20	6	5	6	5.67
21	3	3	2	2.67
22	5	4	7	5.33
23	5	6	2	4.00
24	4	3	7	4.33
25	3	7	3	4.67
26	4	4	6	5.67
27	7	7	1	5.00
28	7	5	6	5.00
29	4	3	6	3.67
30	2	1	4	4.00
31	7	6	7	6.67

Figure 6.2: Results of the Gold-MSI questions regarding musical competency for Participants (Patients) 1, 2, and 3.

ability to judge (See Figure 6.2), Participant 3 had extensive knowledge of musical features indicating "7 - Completely Agree" on questions related to theory and ability to understand qualities of a musical performance. This is most likely stemming from a more than 10-year career in music as a performing harpsichordist. Participants 1 and 2 had no experience playing instruments or with formal music theory training, and listened to only 15-30 minutes of music daily. They indicated negative responses to being able to determine "What is special about a given musical piece (Question 19)," but indicated mostly positively to most questions regarding being able to tell whether music was performed well and in tune and rhythm (Questions 18, 22), and indicated awareness of that they could not sing in-key themselves (Question 10, 17). Based on the lack of theory training, it is expected that Participants 1 and 2 would be able to identify prominent musical features, but perhaps miss smaller and subtler changes in the harmonic structure and rhythm of the piece, where Participant 3 would be able to identify more complex changes.

6.2 Analysis of Valence-Arousal Annotations

Each participant's annotation data was plotted in Matlab as a 3D graph, with time in x-axis, valence on the y-axis, and arousal on the z-axis (See Figure 6.3). Because emotions lie at the intersection of valence and arousal properties (See Section 2.1), it is critical that the analysis of the annotations consider both dimensions together; however, they are displayed with only one variable against time here for the sake of printing and visibility of the entire curve. Within each individual participant's annotation data, key changes (referred to as "Events") were identified. These Events are either sudden peaks in one or both dimensions, indicating a rapid change of felt emotion, or plateaus in the data, which indicate stability through a section. These events were identified visually, based on the plot of each dimension, and labeled with an "Event Number" (See Figures, 6.4, 6.5, 6.6). The first settled value each participant marked after moving at the third clap is labeled as the "Initial" point (as discussed in the annotation method in Section 5.2), a reflection of the baseline emotion felt before the music began.

It is also crucial to note that the events were identified independently from the music, only by working with the annotation data in terms of timed seconds of the recording to ensure that there was no bias towards musical events chosen for examination. After each point was identified, a corresponding approximate emotion was listed based on its values (See Figures 6.4, 6.5, 6.6). Once these events were identified, they became the point of focus and served as anchors for analysis against the music (See Figures 6.7, 6.8). This method was repeated for the tension data, described in Section 6.3.

Full remarks from quantitative data and pedagogical analysis for each Event are noted in detail at the end of this paper (See Appendix C).

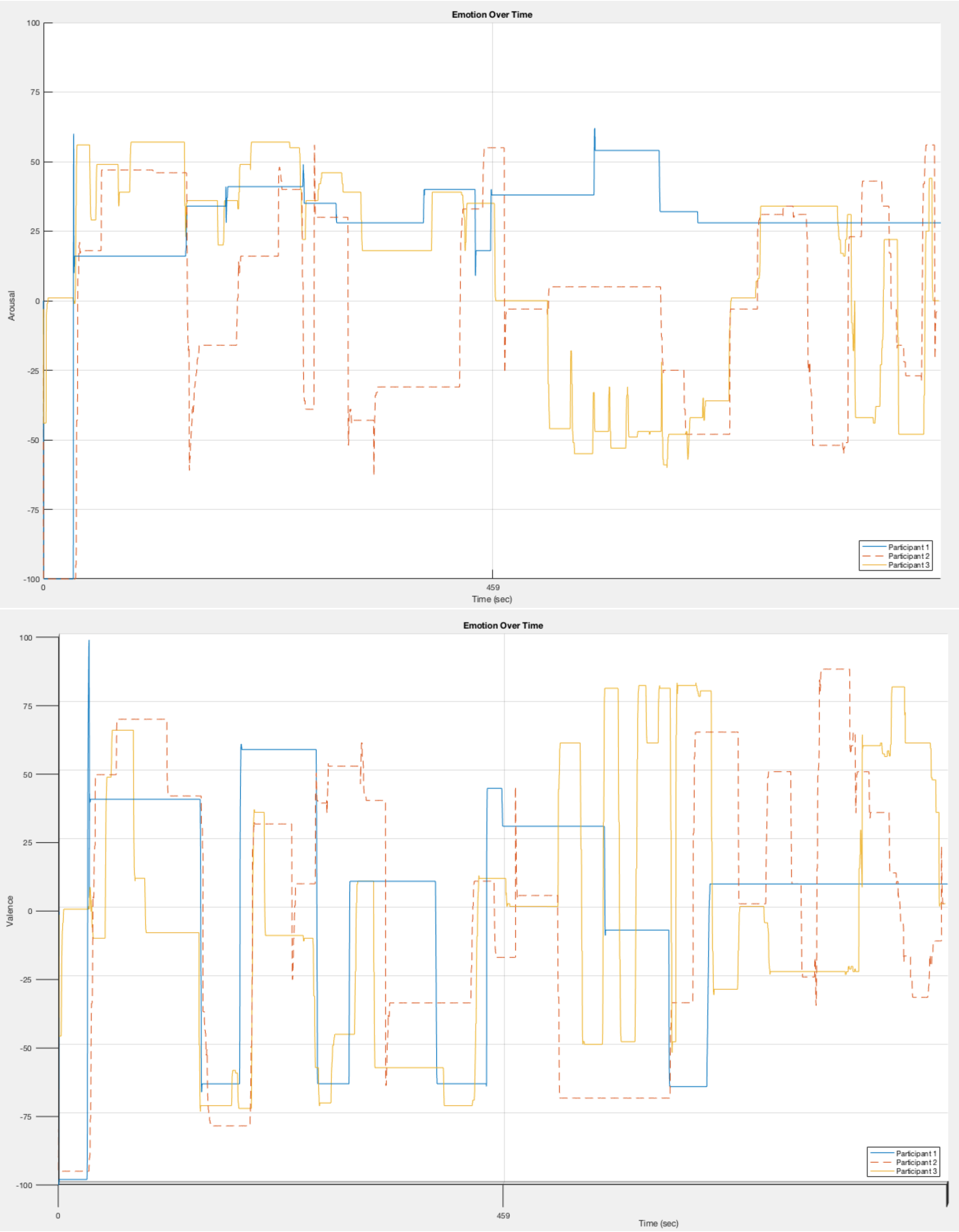
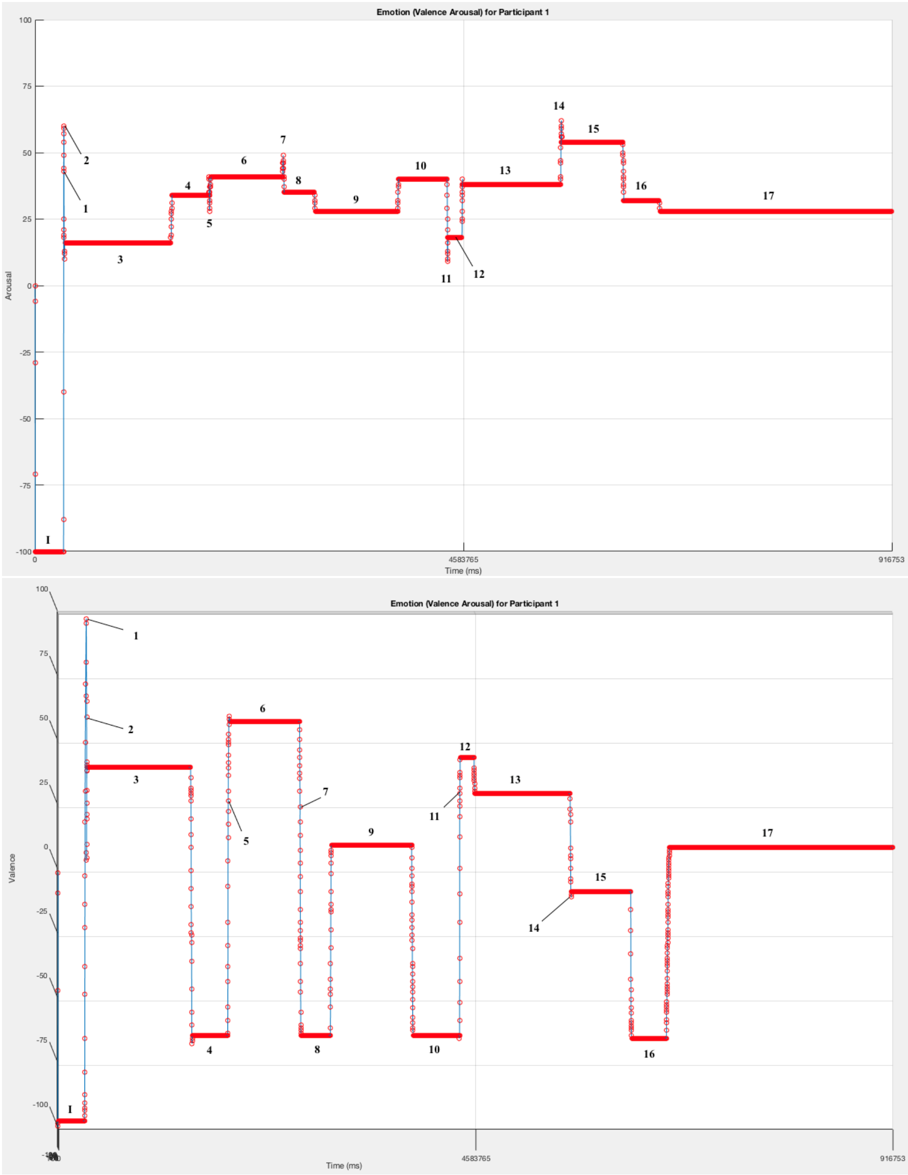
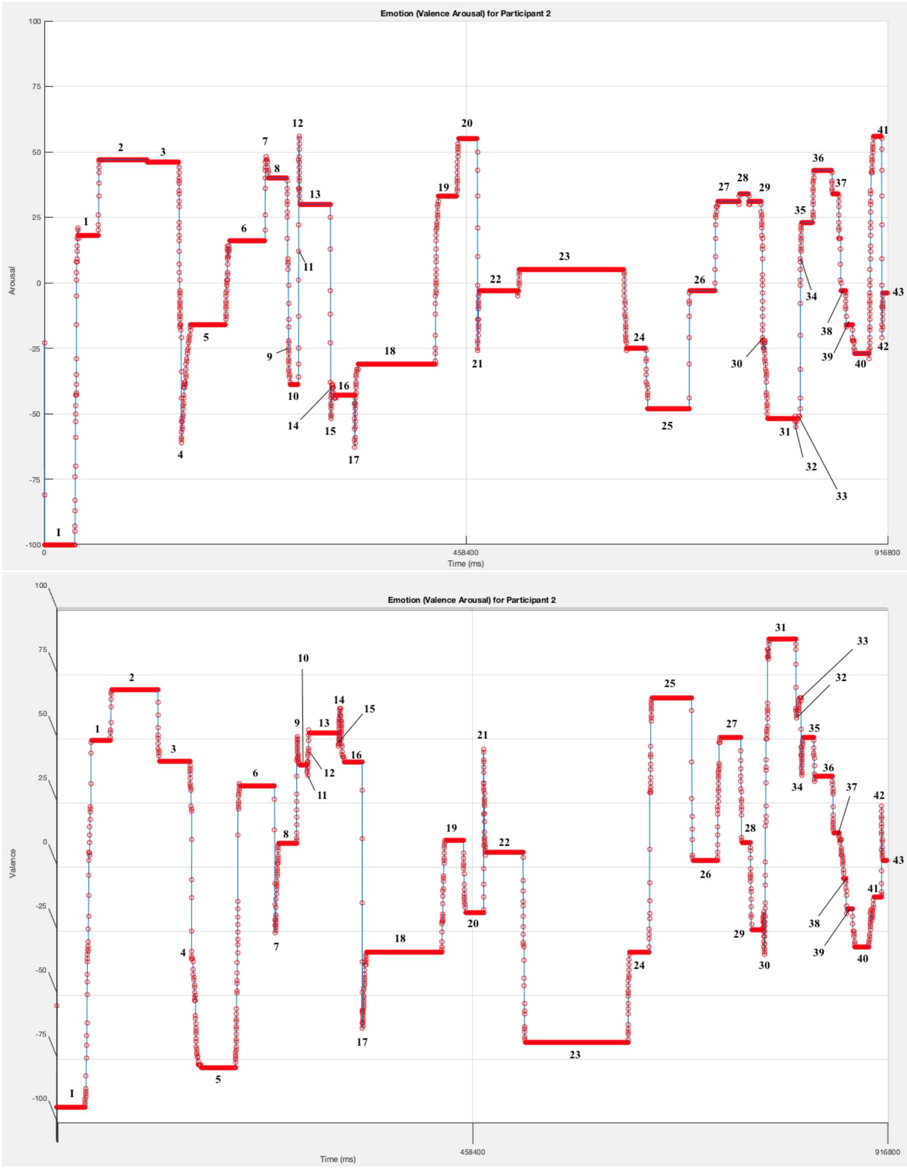


Figure 6.3: Felt emotion annotations over time in the arousal (top) and valence (bottom) dimensions for Participant 1 (solid blue), Participant 2 (dashed red), and Participant 3 (solid yellow).



Sections	Time (sec)	Arousal	Valence	Approximate Feeling
Initial (I)	0.2	-100	-100	Depressed
1	30.701	43	98	Excited
2	30.902	60	60	Happy
3	32.201	16	40	Pleased
4	147.251	34	-64	Agitated
5	186.749	28	27	Surprised
6	188.301	41	58	Happy
7	265.501	49	25	Surprised
8	266.651	35	-64	Agitated
9	299.951	28	10	Surprised
10	389.801	40	-64	Agitated
11	441.451	9	30	Pleased
12	441.852	18	44	Pleased
13	457.751	38	30	Surprised
14	563.151	62	-10	Nervous
15	563.601	54	-8	Nervous
16	629.951	32	-65	Agitated
17	671.551	28	9	Surprised

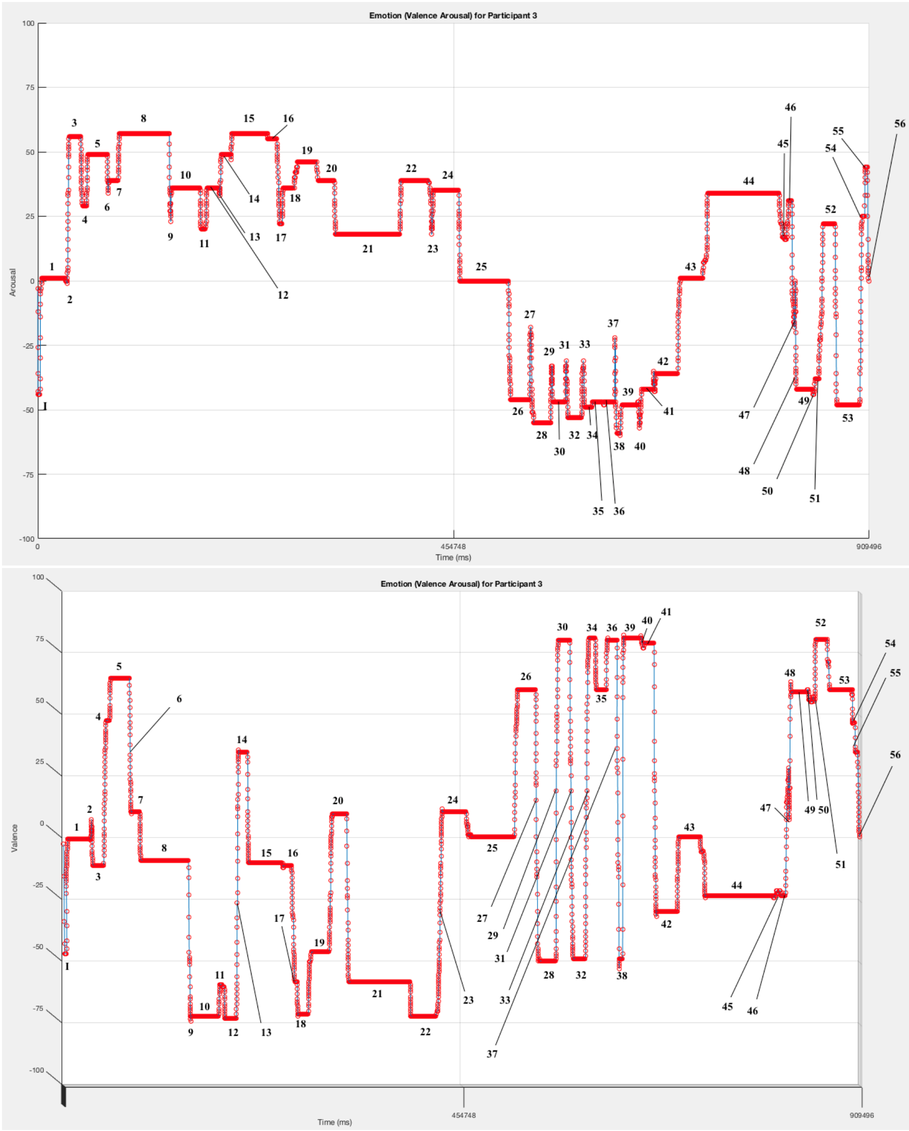
Figure 6.4: Participant 1's arousal (top) and valence (middle) are plotted over time with labeled Events in each dimension. Events are described and numbered (bottom).



Sections	Time (sec)	Arousal	Valence	Approximate Feeling
Initial (I)	0.101	-100	-95	Depressed
1	37.812	18	49	Pleased
2	59.456	47	69	Happy
3	112.111	46	41	Surprised
4	149.101	-61	-37	Bored
5	159.102	-16	-79	Sad
6	201.504	16	31	Pleased
7	240.404	47	-26	Anxious
8	243.956	40	9	Surprised
9	265.65	-25	50	Pleased
10	267.51	-39	39	Content
11	276.557	1	35	Pleased
12	276.858	56	44	Surprised
13	277.763	30	52	Pleased
14	312.659	-39	61	Content
15	311.553	-52	48	Content
16	317.35	-43	40	Content
17	337.654	-63	-62	Sad
18	341.507	-31	-34	Calm
19	428.404	33	10	Surprised

Sections	Time (sec)	Arousal	Valence	Approximate Feeling
20	450.3	55	-18	Nervous
21	471.209	-26	45	Pleased
22	473.051	-3	5	Neutral
23	516.708	5	-69	Disgusted
24	633.309	-25	-34	Calm
25	657.165	-48	65	Content
26	701.911	-3	2	Neutral
27	732.067	31	50	Pleased
28	756.057	34	9	Surprised
29	767.113	31	-25	Anxious
30	781.404	-25	-35	Frustrated
31	786.714	-52	88	Relaxed
32	817.255	-55	57	Content
33	819.952	-51	65	Content
34	822.314	9	35	Pleased
35	823.503	23	50	Pleased
36	836.906	43	35	Surprised
37	857.06	34	13	Surprised
38	867.949	-3	0	Neutral
39	872.154	-16	-17	Calm
40	881.067	-27	-32	Frustrated
41	910.752	-21	23	Content
42	911.959	-4	2	Neutral

Figure 6.5: Participant 2‘s arousal (top) and valence (middle) are plotted over time with labeled Events in each dimension. Events are described numbered (bottom).



Sections	Time (sec)	Arousal	Valence	Approximate Feeling
Initial (I)	0.2509	-44	-46	Calm
1	4.8533	1	0	Neutral
2	31.9989	-1	8	Neutral
3	34.8441	56	-11	Nervous
4	49.1533	29	48	Pleased
5	54.6092	49	65	Happy
6	76.8512	34	34	Surprised
7	78.3073	39	11	Surprised
8	89.4533	57	-9	Nervous
9	145.4518	23	-72	Agitated
10	146.7571	36	-72	Agitated
11	179.0575	20	-59	Frustrated
12	185.1996	36	-73	Disgusted
13	198.9565	33	-26	Anxious
14	201.4	49	35	Surprised
15	212.6464	57	-10	Nervous
16	251.7082	55	-11	Nervous
17	264.5446	22	-58	Frustrated
18	268.7453	36	-71	Disgusted
19	284.2595	46	-46	Frustrated
20	308.058	39	10	Surprised
21	325.8483	18	-58	Frustrated
22	397.1932	39	-72	Agitated
23	430.6988	18	-23	Anxious
24	433.2594	35	11	Surprised
25	462.1456	0	1	Neutral
26	517.5081	-46	61	Pleased
27	538.7962	-18	22	Pleased

Sections	Time (sec)	Arousal	Valence	Approximate Feeling
28	542.545	-55	-49	Bored
29	561.8583	-33	20	Content
30	563.5486	-47	81	Relaxed
31	561.9587	-31	32	Content
32	580.5021	-53	-48	Sad
33	596.7527	-31	40	Content
34	598.694	-49	82	Relaxed
35	607.0956	-47	61	Relaxed
36	620.3001	-47	81	Relaxed
37	631.396	-22	37	Pleased
38	633.0028	-57	-52	Bored
39	638.944	-48	82	Relaxed
40	658.2572	-57	82	Relaxed
41	662.2069	-42	80	Relaxed
42	676.3487	-36	-29	Calm
43	702.7581	1	1	Neutral
44	733.6525	34	-23	Anxious
45	811.6086	27	-24	Anxious
46	821.5998	31	-23	Anxious
47	827.3068	-18	29	Pleased
48	829.3486	-36	64	Pleased
49	829.8507	-42	60	Content
50	847.9087	-44	60	Content
51	852.2099	-38	56	Content
52	859.4565	22	81	Happy
53	873.7992	-48	61	Content
54	904.593	29	45	Pleased
55	904.9949	44	35	Surprised
56	908.9447	0	2	Neutral

Figure 6.6: Participant 3‘s arousal (top) and valence (middle) are plotted over time with labeled Events in each dimension. Events are characterized and numbered (table, bottom).

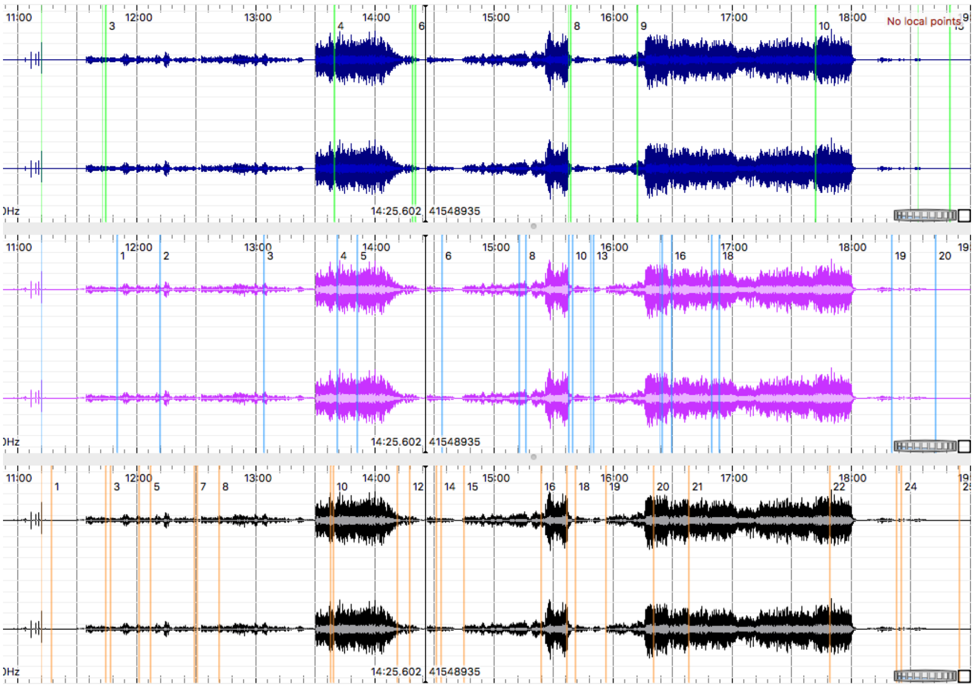


Figure 6.7: Key annotation events marked as Time Instants against the audio signal in Sonic Visualiser for Participants 1 (top, green verticals), 2 (middle, blue verticals), and 3 (bottom, orange verticals).

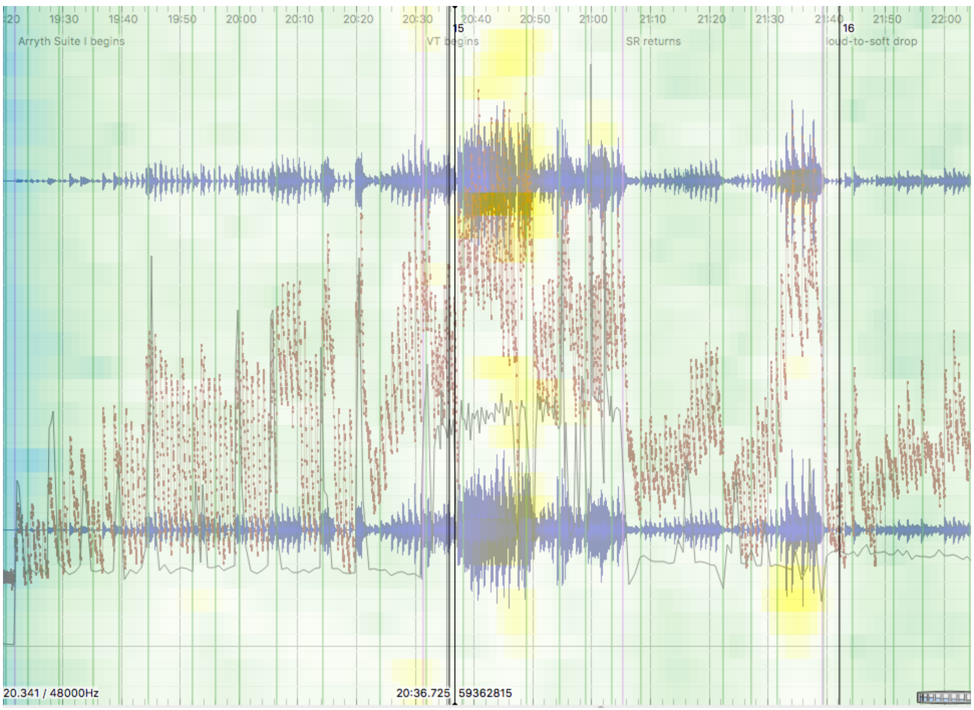


Figure 6.8: A section of the Sonic Visualiser window at the start of VT "before during after" with Participant 1's Valence-Arousal Events 15 and 16 (black verticals) against Cyclic Tempograms (blue to yellow 3D color plot), tempo (black line), loudness values (red points), loudness change points (green verticals), and performer boundaries (purple verticals)

6.2.1 Participant 1

Participant 1 indicated the fewest valence-arousal changes overall, with a total of 17 major events indicated in the annotation (See Figure 6.4). The Initial marking at 0.2 seconds after the third clap indicated a base feeling with highly negative value in both valence and arousal, an emotional equivalent being "Depressed."

There are no events marked through the duration of *VT before after UNI* (Chopin); it appears the participant stopped annotating at the end of the *VT before during after*, although it is not known why. Of the 17 annotation events in the other two pieces, 12 occurred at a significant focused musical event - 6 occurred with a loudness feature (50%), 8 with tempo/pulse (∼67%), and 11 with a harmonic or note density feature (∼92%). This participant did not annotate change in felt emotion at all section changes, but seemed to commonly feel strong feelings of "Agitation" and "Surprise" with unexpected chord structures. Positive feelings and pleasure were associated with repetition in the main theme and in expected harmonic structures with a focus on melody in the treble line.

6.2.2 Participant 2

Participant 2's annotation had a total of 42 major events through the performance (See Figure 6.5). The Initial event (0.101 seconds after the third clap) was similar to that of Participant 1 – highly negative in both dimensions with an approximate feeling of "Depressed."

Of the 42 annotations, 38 occurred with at least one of the focused musical features: 18 with loudness (∼7%), 26 with tempo/pulse (∼68%), and 29 with harmonic/melodic features (∼76%). This participant seemed especially effected by violations to the harmonic structure, with none of the 29 Events of the harmonic/melodic feature category occurring with melodic violation alone, as seen prominently in Participant 1's annotations. Dissonance caused stronger discomfort for this participant, with feelings like "Disgust" and "Frustration" in the long sections of harmonic dissonance in *VT before during after* and *VT before after UNI*. The rhythmic instability in *VT before after UNI* was only aligned with negative feelings when the harmonic structure also was unstable; otherwise, the participant favored positive response in both dimensions, even with the tachycardia rhythm occurring. Similarly to Participant 1's annotation, stability in a section led to a plateau in the data, with sections of familiar motifs and major mode producing the most positive feelings.

6.2.3 Participant 3

Participant 3, with the most musical experience of the test group, also indicated the most Events in the annotation, with 54 total (See Figure 6.6). The Initial Event (0.2509 seconds after the third clap) leaned negatively in both dimensions, although not as strongly as the first two participants, for an approximate feeling of "Calm."

Of the 54 Events in the annotation, 43 occurred with at least one of the focused musical features: 19 with loudness (∼44%), 25 with tempo/pulse (∼58%), and 22 with harmonic/melodic features (∼51%). Participant 3 seemed to be the least focused on loudness changes and melodic features (with only two of the Events occurring on a focus in dissonance or distance in the melodic line). Harmonic instability alone (especially in the end of the *VT before during after*), while noticed in the annotations did not often produce negative valence and arousal and favored feelings of "Calm" and "Content;" perhaps, with Mars being a well-known piece amongst musicians and with the repetitiveness of the dissonances, the harmonic violations and unclear structure were not enough to cause discomfort. As with the others, plateaus in the annotation occurred with areas of repetition and in stable rhythmic and/or major feel.

6.3 Analysis of Tension Annotations

In the same method of analysis, Events were identified in each of the participant's annotation markings and examined against the music in SV (See Figures 6.9, 6.10, 6.11, 6.12). Events in the tension annotation also include examination of sudden changes and plateaus of consistent felt tension. Some small peaks occur in the annotation (<5 points away from surrounding significant annotation) and are not examined; they are likely not corresponding to intentional movement and are only due to the clicking or releasing of the mouse on the slider. These points, along with those marked during periods of silence, are noted in the full analysis (See Appendix D).

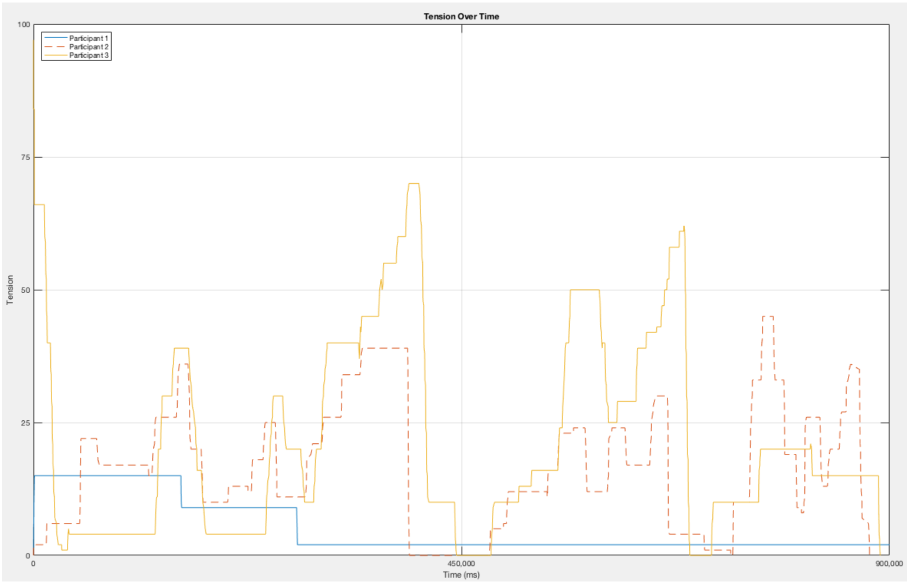
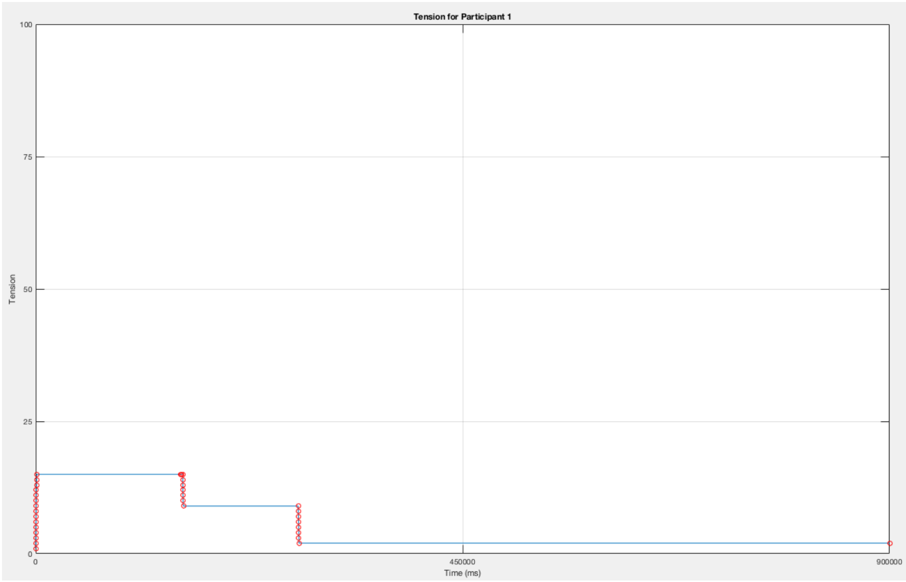


Figure 6.9: Tension annotations over time from Participants 1 (solid blue), 2 (red dashed), and 3 (solid yellow).

6.3.1 Participant 1

Participant 1 marked only two major changes through the duration of the performance, both during *Ballade No. 2* (See Figure 6.10). Professor Chew confirmed that the participant had no issue operating the software and that the participant remarked they were just "not really ever stressed." The Initial marking just after the clap had a baseline tension of 15. The two changes to felt tension do occur at expected places: during the first storm section of *Ballade No. 2* and just after at the transition back into the triplet theme. This would indicate that Participant 1 was most impacted by the changes to loudness, as tempo and melodic/harmonic features appeared at least one musical phrase before the annotation was marked; however, this may be due to delay in using the interface. Because there are no other markings, it is difficult to conclude any patterns about this participant's felt tension, except that there were no changes in the *Arrhythmia Suite* pieces that felt strong enough to warrant any marking.



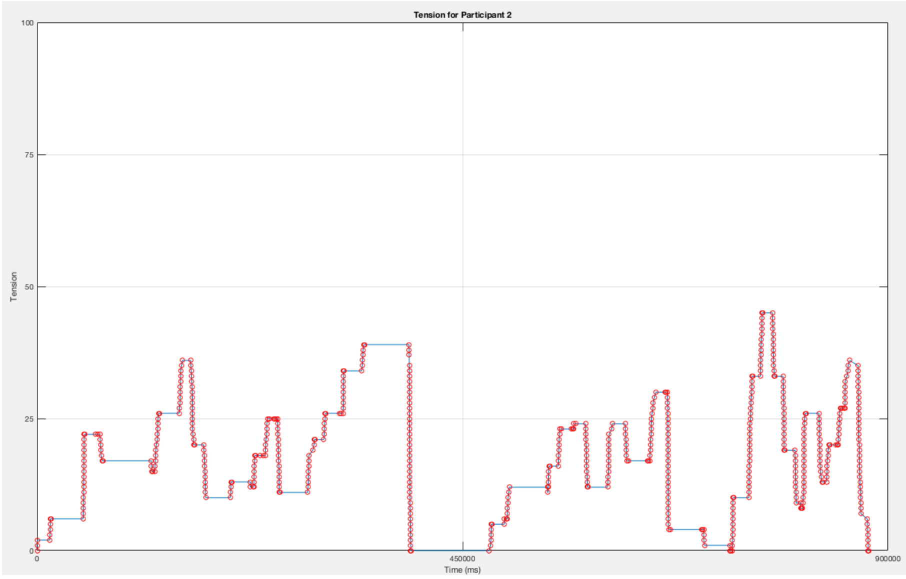
Event	Time (sec)	Value
Initial (I)	0	15
1	155.121	9
2	276.77	2

Figure 6.10: Participant 1's tension annotation (top), with table of significant change Events (bottom).

6.3.2 Participant 2

Participant 2 marked a total of 46 different tension ratings during the course of the full performance (See Figure 6.11). Three occurred during points where there was no music, and 8 were ignored as insignificant movements, leaving 35 for further examination – 22 increases and 13 decreases. The Initial marking indicated a base tension of 2.

Events where there was an increase in tension corresponded most with sudden jumps and rapid fluctuation in tempo, with 14 of the 22 increases having this element (~64%); 10 had a loudness change point with either a sudden reduction or increase in loudness (~45%), and 12 had a relation to a harmonic or melodic event (~55%). Further refining the harmonic/melodic category, 11 occurred with harmonic dissonance and violated chords, 1 with violations of resolutions in the melodic line, and 1 with both features.



Event	Time (Sec)	Value
Initial (I)	0	2
1	13.583	6
2	49.651	22
3	68.714	17
4	120.787	15
5	128.229	26
6	152.963	36
7	164.985	20
8	175.778	10
9	204.588	13
10	225.096	12
11	229.739	18
12	243.191	25
13	255.47	11
14	292.763	21
15	304.293	26
16	323.645	34
17	345.253	39
18	394.626	0
19	479.873	5
20	493.586	6
21	498.69	12
22	539.373	11
23	540.878	16
24	552.25	23
25	567.187	24
26	581.454	12
27	607.644	24
28	623.319	17
29	653.823	30
30	667.909	4
31	705.13	1
32	732.398	0
33	735.326	10
34	755.346	33
35	766.125	45
36	779.123	33
37	789.319	19
38	802.089	9
39	806.82	8
40	811.996	26
41	829.314	13
42	837.138	20
43	849.057	27
44	858.616	36
45	870.572	7
46	878.454	0

Figure 6.11: Participant 2's tension annotation (top), with table of significant change Events (bottom).

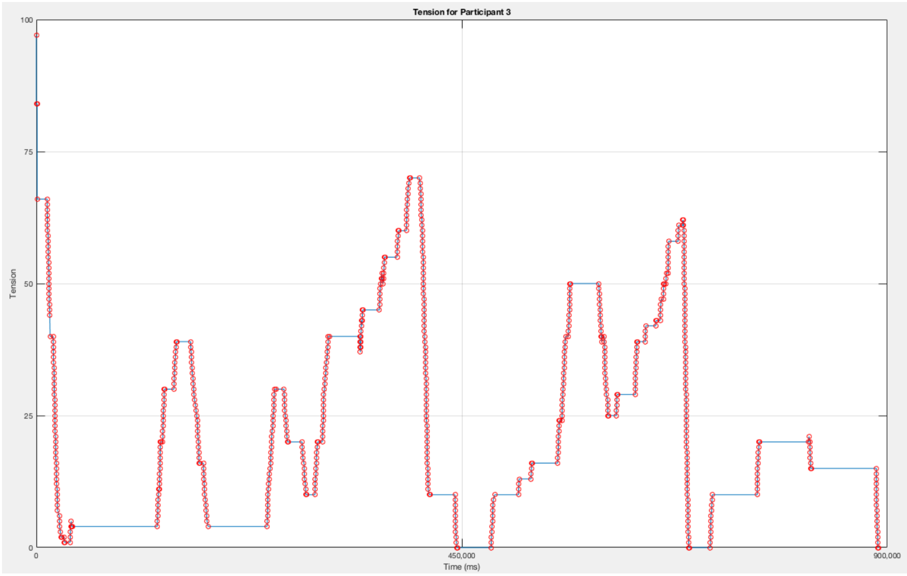
The decreases in tension showed correlation to stable rhythm and chord structure, with decreases during repetitive phrases – all 13 decreases occurred against a feature that had been previously encountered in the piece or in the middle of a repetitive section with stability in tempo. Loudness seemed to have no impact on decreases, with only 1 of the events occurring against a loudness decrease. Apart from the original storm section at the start of the Chopin, the other storm section transitions seemed to produce decreases in tension, perhaps with familiarity of the section repetition.

Most interesting in this participant‘s annotation was the comparison of features between *Ballade No. 2* and *VT before after UNI.* In the ballade, there was a heavier focus on the harmonic and melodic features for tension; in the same events in the arrangement, rhythmic instabilities were the focus. Phrase ends that were harmonically stable and had expected resolutions had increased tension if they were accompanied by interrupting rhythmic features, and the final storm section produced decreases in tension with a stable rhythm. This may also be due to the familiarity of the harmonic and melodic features, which were heard earlier in the performance. This contrasts with the valence-arousal interaction, where the participant reacted negatively to the rhythmic instability only when harmonic instability was also present.

6.3.3 Participant 3

Participant 3 indicated a total of 50 events in the tension marking (See Figure 6.12), with 4 changes being marked during silence and 14 insignificant points being ignored during analysis. Of the 32 thus examined, 21 were increases to tension. Loudness seemed most responsible for these increases, with 15 of the events having a sudden loudness change in either direction (∼71%). Tempo presented mostly in the *Arrhythmia Suite* pieces but seldom in *Ballade No. 2*, with tempo features appearing in only 7 of the changes (∼33%). Harmonic and melodic violations accounted for components in 8 (∼38%) and 7 (∼33%) of the tension changes, respectively. In these cases, only dissonant harmonic line or chord violations were related to increases in tension.

In the case of the 11 decreases, there was a notable pattern of stability behind the annotation, as all but one annotation was in a section featuring the motif or in repetitive rhythm and resolved chord progression. This exception was Event 15, which was marked just as a storm section transitioned before the triplets reentered, and featured some unexpected resolutions in the melody line. Consistent loudness appeared as a feature in 5 of the Events (∼45%), consistent tempo/pulse, resolved harmonic progression, and resolved



Event	Time (sec)	Value
Initial (I)	0	66
1	13.693	40
2	25.229	2
3	28.838	1
4	35.99	5
5	36.619	4
6	128.523	11
7	130.406	20
8	134.434	30
9	147.255	39
10	171.21	16
11	180.742	4
12	251.474	30
13	264.946	20
14	284.241	10
15	296.637	20
16	307.941	40
17	341.81	37
18	343.295	42
19	344.19	45
20	364.558	52
21	365.68	50
22	367.298	55
23	382.129	60
24	393.876	70

Event	Time (sec)	Value
25	414.788	10
26	444.054	0
27	483.812	10
28	509.644	13
29	523.046	16
30	552.208	24
31	558.824	40
32	563.641	50
33	596.99	39
34	597.214	40
35	603.607	25
36	613.099	29
37	634.198	39
38	643.645	42
39	654.467	43
40	659.78	47
41	662.63	50
42	665.383	52
43	667.732	58
44	682.752	62
45	689.141	0
46	713.888	10
47	763.423	20
48	816.204	21
49	817.965	15
50	889.366	0

Figure 6.12: Participant 3's tension annotation (top), with table of significant change Events (bottom).

melodic progression each with 6 Events (∼55%). Participant 3 also did not appear affected by chromaticism in the melodic line, with this feature appearing in both increasing and decreasing sections of tension; other participants felt the chromatics more associated with increases in tension.

Participant 3's annotations also more closely resembled the Performer Boundaries in the piece than the other two participants; that is, there was more reaction to the events within each piece that the pianist uses to structure expression during the performance. This is possibly related to Participant 3's personal experience as a performer and awareness of the sectioning of each piece, which contributes to the emotional progression of the music.

6.4 Analysis of Transitions and Sudden Change Markings

Because of the nature of the annotations for transitions and sudden changes, each marking was examined individually. Participants had the ability to label their annotations as being either "sudden changes" or "transitions," during the assisted marking. In some cases, the length of a sudden change was more indicative of a transition – this factor is ignored in favor of the participant's personal definition of the event. The goal was to determine what occurred at each sudden change or during each transition (if the annotation aligned with a musically salient section), and why the participant deemed it notable. Annotations were examined against the audio of the performance (Figure 6.13) with the focused musical features (See Appendix E).

6.4.1 Participant 1

Participant 1 did not mark any changes or transitions during *VT before during after*; based on the other two pieces, it appears that the annotations aligned with some significant musical transition. It is unclear why the second piece received no attention in the annotation, although the Holst has a much looser structure than the Chopin, which has the clearly defined motif and "storm" section of unrest, and goes back and forth between the two. The Holst transitions in a more linear way, with different sections that become more unfamiliar until the conclusion, where the opening statement is repeated in variation. In this observation, it appears that the participant reacted strongly to the

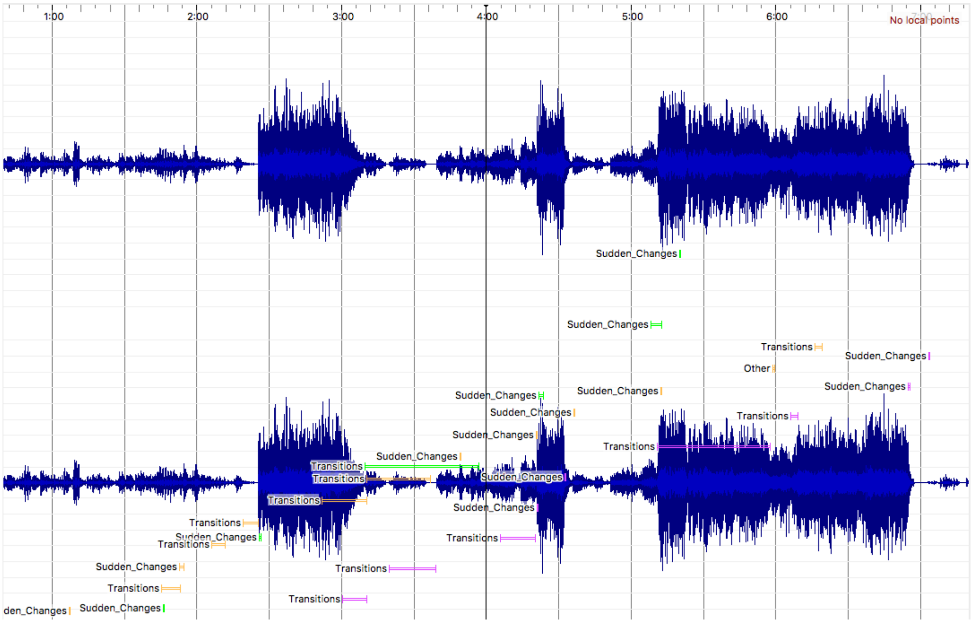


Figure 6.13: A frame from Sonic Visualiser displaying some of the ELAN transition and sudden change markings (Participant 1, green; Participant 2, orange; Participant 3, purple against the performance waveform.

familiarity of the sections through both variations of the Chopin, but perhaps could not determine sections within the *VT before during after*.

All 7 sudden changes in the other two pieces marked by Participant 1 were either notable dissonances in a motif section or loudness changes (often accompanied by chromatically ascending melodies) at the start of a storm section. This indicates that the participant had a grasp on the contrasting themes through the piece and reaffirms that dissonance in the triplet theme caused sudden emotional response. Only two transitional periods were marked (one in each piece); the transition in *Ballade No. 2* is quite long and spans the entire composed transition out of the first storm section back into the triplet motif, ending just as another unexpected dissonance appears in the prominent bass melody. The transition in *VT before after UNI* also captures a transition out of the storm section at the end of the piece in the chromatic bass line, just before the triplets briefly return at the end. The end point of the transition is opposite here (back to the motif, versus the dissonance in the first transition), and does not indicate much about what caused the feeling of transition; however, it is notable that the first transition spans a section change and is bookended with two dissonances.

6.4.2 Participant 2

Participant 2's 14 marked sudden changes occur in a wider range of musical events, the most being at a sudden dynamic change (7 changes, 50%). Six of these dynamic changes occur at a boundary between sections (for instance, in *Ballade No. 2* at the chromatic ascending lines approaching the loudness change at the start of the storm, or sudden reduction to the loudness upon returning to the triplets), while one in *VT before during after* coincided with a sudden staccato articulation. Two additional marked changes occurred at the start of the second and third pieces (∼14%), and could be included in the dynamic change category, being transitions from silence. Dissonance occurred in 4 marked changes (∼29%). One non-dissonant change occurred, interestingly, at an arpeggiated chord in the middle of a phrase (∼7%). Other than this one instance, the participant appeared to define a sudden change as a dynamic change (often at the start of a section) or dissonance.

Of the 12 marked transitions, 2 occurred at places of non-significant musical change (∼17%). One of these took place within the first triplet section in the ballade, and a second within the final storm section (this may have been a reaction to increased distance between the bass and treble voices, but the transition does not align well enough with the jump in the treble voice's pitch to say for sure if that was the influence). One transition also occurs in a dissonant section of Mars, where staccato dissonant chords are repeated, but no major musical transition occurs in the progression of these specific chords that would distinguish them from the others in surrounding measures.

Another interesting transition occurs in the *Arrhythmia Suite* arrangement of the ballade: a 26-measure transition goes completely through the triplet section and ends at the fermata just before the first storm, seeming more like a section definition than a transition. This marking, along with another 8 of the transitions (75%), only had a noticeable feature of ending with defined sections in the piece. These transitions started at seemingly arbitrary points, but the marked end points coincided with the end of a phrase. This is perhaps an indication that the participant found it difficult to determine where the transition started but was able to relate features such a resolution of a chord structure and return to *a tempo* themes as an end to a section.

6.4.3 Participant 3

Participant 3 indicated an equal number of sudden changes and transitions through the performance - 10 in each category. 9 of the sudden changes occurred at the beginning of a marked score section or end of a musical phrase (90%); the other occurred at a dynamic increase in the bass melody in middle of a section in *VT before after UNI*. The sudden changes were predominantly aligned with loudness changes (90%): four of these were a solely dynamic change (40%), while others were accompanied by features such as dissonance (40%), and resolution in a return to motif in the triplet theme (10%). The other sudden change occurred at the major resolution of the final chord in the conclusion of *VT before after UNI* (10%).

Transitions marked by Participant 3 all occurred alongside loudness changes where a melodic feature was highlighted (where the melody is passed back and forth between prominent treble or bass voice). This particularly occurs in the chromatic lines that ascend/crescendo or descend/decrescendo out of the storm sections in the Chopin and its arrangement (50%). Another takes place in the return to the triplet theme before the long fermata pause (10%) and the final measure of bass melody before the *Agitato* section in the final storm of *Ballade No. 2* (10%). In *VT before during after*, two transitions occur around crescendos in dissonances between spread bass and treble voices before the lines descrescendo (20%). The final transition also focuses on melodic line in *VT before after UNI*, when the treble takes over the melody in a variation of the triplet figure (10%).

7 Results

Based on the analysis of the musical features occurring at the change points discussed in Chapter 6, several conclusions can be drawn from the feelings and annotations marked at those points. Not every pedagogical change point through the performance was noted, but the vast majority of the markings occurred at a point of some musical significance.

In all of the annotation methods, the most common feature between participants was that repetition, regardless of the features involved, produced feelings of contentment or pleasure and low tension. This is notable in the storm theme within *Ballade No. 2* and *VT before after UNI*, and in the repetitions of staccato dissonances in *VT before during after*.

Feelings of “Surprise“ and “Agitation“, and high tension were made alongside *(1)* sudden loudness changes, *(2)* sudden dissonances, or *(3)* sudden tempo increases and rapid pulse fluctuations.

Feelings of “Pleasure“ and ”Happiness”, and low tension were common around *(1)* expected, major chord progressions, *(2)* stable tempo, and *(3)* stable loudness levels.

In those sections originally causing “Surprise,“ “Agitation,“ and high tension, if the features of the section progressed through more than four complete phrases, or the section was presented again later in the piece, the ”shock” factor was lost. Annotations of these tumultuous sections generally settled to “Content“ feelings and remained stagnant through the remainder of the section. This indicates that the participants could:

1. Identify sections and their boundaries
2. Remember themes and patterns from earlier in the composition.

7.1 Valence Arousal Conclusions

In the data collected in the dimensions of valence and arousal, the following conclusions can be made:

- The best way to induce a change to emotion through music is to focus on features in the harmonic structure (in Participant 1 and 2‘s annotation events, the majority had a harmonic feature; Participant 3‘s had tempo or harmonic features).
- Major tonality and normal progressions in the Western canon created feelings of “Pleasure“ and “Contentment.“
- Resolutions of dissonances back into a familiar cadence, or from minor into major (as in the end of the *Arrhythmia Suite* arrangement of the Chopin), produce high feelings of “Satisfaction“ and “Pleasure“.
- Sudden jumps in loudness (such as the first storm section of the Chopin), whether soft-to-loud or loud-to-soft, create negative feelings, mostly “Agitation.“
- Repetition, regardless of the feature being repeated, creates some sense of stability. The shock factor of the storm theme, in particular, loses its potency as it is repeated.
- In order for loudness alone to cause a change in valence-arousal space, there must be a shock factor: introduction to new material or unexpected variation in the structure of a repeated section.
- Slow increases in loudness (such as the storm section transitions with rising chromatic lines) create feelings of “Nervousness.“
- Sudden tempo changes and fluctuations, like those from the arrhythmia patterns, caused negative feelings of “Nervousness,“ “Anxiety,“ and “Frustration.“

7.1.1 Musical vs. Non-Musical Background

Conclusions regarding listeners with musical vs. non-musical backgrounds include:

- Sudden violations of the chord progression caused sudden changes in all listeners, regardless of musical background.
- In listeners with non-musical backgrounds, harmonic dissonance induced negative felt emotion consistently.

- In a listener with musical experience, however, harmonic dissonance only caused discomfort when combined with other features. The features were noticed in the annotations, but feelings of “Neutrality,“ “Calm,“ and “Contentment“ were still common.

- In a listener with musical experience, melodic deviations caused change much less than in those with non-musical backgrounds (confirming studies by Bigand [25] and Farbood [29]), and did not induce negative emotion when they occurred on their own.

7.2 Tension Conclusions

There is less data to support conclusions in felt tension due to Participant 1‘s limited annotations. There is less of a correlation across participants, as in the case of the valence-arousal space previously discussed in Section 7.1. Based on the felt tension data available, the following conclusions can be made:

- Periods of stability and familiar patterns produce decreased tension; for instance, reintroduction of the storm theme produced a decreased tension with each appearance.

- Sudden changes in loudness or tempo, create sudden increases in tension.

- Harmonic and melodic progressions caused tension increases over longer observation periods (confirming Farbood [30]).

- As the note positions move further from the tonal center, tension increased, demonstrating that the listener was able to relate the current musical event back to a feeling of harmonic or melodic stability (confirming Lerdahl and Krumhansl [5] and Farbood [30]).

The most convincing argument for repetition‘s impact is found in tension data. In *VT before after UNI*, participants focused less on harmonic and dynamic changes as a source of tension, and very heavily on the tempo fluctuations in the tachycardia rhythms. Tension increased with tempo fluctuations, even when harmonic and loudness stability were present; on the other hand, the final storm section, which does not include this tempo variability, coincides with decreases in tension, despite having many harmonic violations and loudness features. This further supports the idea that familiarity (having heard *Ballade No.2* prior in its original form and encountering the storm theme multiple times by the end of the 15-minute performance) reduces tension, despite the same features producing tension in previous sections.

7.2.1 Musical vs. Non-Musical Background

There were no significant differences between the musical and non-musical participants in felt tension annotations.

7.3 Transitions and Sudden Changes

Conclusions regarding felt transitions and sudden changes include:

- Both transitions and sudden changes fell in line with composed section boundaries, often labeled lettered sections in the score, meaning they also occurred with notable sectioning as indicated by the composer.

- Loudness changes were highly present against marked sudden changes. Loudness changes are used frequently to highlight the contrast between musical sections (especially in the Chopin).

- Transition annotation end points were consistent with composed section transitions.

- Participants have difficulty defining where a transition begins; there is some ambiguity within each participant‘s annotation about what features define the start of a transitional period.

7.3.1 Musical vs. Non-Musical Background

There are few consistencies within the annotations of the two participants with less musical experience, so it is difficult to identify any patterns or relate them to each other.
Participant 1 had unclear motives behind their marked transitions, with one spanning through entire motifs in the ballade. The beginning and end of the two marked periods do not align with any reasonable musical events. The first transition is bookended by two dissonant points, indicating that the participant could tell there was a notable change; its unclear, however, why they were deemed transitions based on the other musical surroundings. Transitions marked by Participant 2 contained some ambiguous starting points, but end points aligned well with composed section boundaries, suggesting they were able to understand where one section began and another ended. The reasoning behind the starting points of the transitions is unclear, however.
It is notable that Participant 3, with more musical knowledge, marked transitions alongside loudness changes where a voice became prominent in the melody, indicating that the movement of a leading voice defined the outline of a transition. This is contrary to the felt valence-arousal and tension annotations, where melodic features were less present in the markings made by someone with more music knowledge.

8 — Conclusion

This thesis has explored a wide range of data from participant annotations to determine how features in a live music performance impact felt emotions. Annotations of felt emotion in a valence-arousal space, tension, and transitions and change points during the performance give a broad view of how listeners interact with and experience music.

This thesis began by providing a comprehensive look at the way music and emotion are related, and how the act of listening to music is a truly individual experience, which combines musical features with the listener's background to produce unique emotional context. A selection of related studies in the field of music cognition were presented to provide a point of reference for the exploration of felt emotion in this study.

Several pieces of software were used to collect annotation data from participants. An explanation of the interfaces and development was discussed, followed by the procedure for conducting the live music performance and participant annotations.

Features of the loudness, tempo, and harmonic and melodic structure of the three pieces have been quantified and described in a pedagogical music theory examination. Software used for qualitative analysis was described and a summary of the music and annotation data analysis is discussed in detail before conclusive results of this study, outlined in Chapter 7.

By mapping the felt emotion annotations of participants to the music data, other studies in music cognition have been affirmed and the current knowledge of emotion can be extended to include these patterns in felt emotion caused by live music performance. This data will be used in *Cardiac Response to Live Music Performance* study, described in Section 8.2, and as a basis for other related studies in music cognition, especially those focusing on felt emotion.

8.1 Considerations for Future Work

As the first test in this larger research project, it was only possible to recruit three participants fitting the criteria for the study within the time line. In another iteration, it would be ideal to include more participants to examine patterns across a larger data pool and within larger musician and non-musician subgroups.

It would be ideal to include an ensemble performance in future studies to provide more musical features for examination; for instance, including ensemble pieces with different instruments would allow examination of varying timbres, as examined in the studies by Farbood [28, 29, 30] discussed earlier in this paper.

The final point to be considered in the future is the inclusion of data from the MorpheuS Tension Visualiser, which was eventually omitted in later stages of the analysis for this thesis. The software is designed to work with small excerpts of music to produce a tension value for each beat; in analysis for this study, the resulting data gave values for a number of beats inconsistent with the actual number of beats in the piece. Attempts to align these data values with the time values of the beats ultimately failed because it was not possible to determine which beats the data values corresponded to. This made it impossible to align participant annotations and audio from the performance to the tension values calculated from the score. In speaking with Dorien Herremans, this may be due to the fact that what “the parser doesn’t take into account is meter changes, as we take 1 value for the whole song, this is something for future implementation.” The original study used excerpts without meter changes to accurately calculate the tension per beat [48].

Ultimately, this study used only a pedagogical analysis for harmonic and melodic features, and did not work with quantitative data in examination of this feature only. This research will continue working with MorpheuS to create a tool for analyzing entire pieces; music analysis by humans still outperforms any existing analysis software, but the value of quantitative data to support qualitative analysis is invaluable.

8.2 Continuation of *Cardiac Response to Live Music Performance*

The conclusions from this study will be part of the larger *Cardiac Response to Live Music Performance* study, as discussed before. The conclusions of the annotation data and the music analysis will be examined against the heart data collected during the live performance to determine *(1)* how these musical elements cause emotional impact to the nervous system to stimulate the heart's response, and *(2)* whether participant-indicated felt emotion accurately reflects the autonomous response of the body.

This research aims to provide additional information about the degree to which vicarious emotions experienced through music compare to the effects of emotions in other contexts (ie. the stressors experienced in daily life) and how they impact one's health. It will also aim to improve the feasibility of mapping electrophysiological changes in the heart to change points and transitions in a musical stimulus, and contribute to the current understanding of pathways that affect mood and how heart rhythm is impacted in response.

With advances in this knowledge, the hope is to propose alternative, non-pharmacological approaches for treating the effects of stress, especially for patients like those involved in the study who are using pacemakers, or for those who currently receive a form of pharmacological therapy to treat health conditions caused by stress. It is also hoped that more links between perceived and felt emotion and physiological response will be documented and thus increase the understanding of how cardiac episodes are triggered, aiding prevention and early-detection of life-threatening cardiac events.

Participant Information Sheet and Informed Consent Form

Study Title (short): ***Cardiac Response to Live Music Performance***

Study Title (long): Effect of Musical Changes and Transitions in Live Music Performance on Cardiac Electrophysiology as Quantified in Patients with Biventricular Pacemakers or ICDs

Study team:

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Part 1 of the Participant Information Sheet

1. Invitation and brief summary

You are invited to participate in a study to determine the effect of live music performance on the electrical behaviour of listeners' hearts.

Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully and discuss it with friends, relatives and your GP as you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

2. Purpose and background

Mental stress as well as physical stress can result in abnormal heart rhythms, which in some people may be dangerous. Relatively little is known about mental stress and the way in which it affects the heart. We know that the heart muscle cells create minute electric currents, which then travel in coordinated waves across the heart to make the heart beat. If these waves become very uneven, abnormal rhythms may result.

We believe that mental stress may destabilise these electric currents, but we do not know how. The purpose of the studies we are undertaking is to record the electrical waves while at the same time creating mild mental stress through music.

3. Why have I been contacted?

We are asking patients to participate who have been fitted with a special pacemaker such as yours. This enables us to record the electrical waves directly from the heart from one of the electrodes used for pacing.

4. What would taking part involve?

We will invite you to attend a short classical music performance at St. Bartholomew-the-Great Church. The site was selected because it is a concert venue and has a good quality grand piano, and it is located next to St. Bartholomew's Hospital. The site was not selected for any religious reasons.

You will be sitting comfortably in a chair during the performance by a piano trio lasting about 15 minutes. Parts of the music may be mildly stressful and parts of it lush and pleasant.

Before the performance, we will also programme your pacemaker or ICD to a normal rate so that any changes induced by the music can be accurately measured. We will also ask you to complete a questionnaire that will help us gauge your level of music listening experience.

While you are watching and listening to the performance, we will record the electrical signals from your pacemaker or ICD.

The performance you hear will be recorded, and replayed to you three times, during which you will be asked to recall and rate: (i) the emotions you felt during music listening; (ii) the degree of tension/stress you experienced during music listening; and, (iii) where you sensed important changes or transitions in the music.

The entire study—including filling out the questionnaire, listening to the performance, and rating the performance—should take about 75 minutes.

If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

5. What are the possible benefits of taking part?

We cannot guarantee any therapeutic benefits of taking part in this study. However, the outcomes of this study will help us better understand the connection between emotions and heart electric signals. This knowledge may help us propose non-pharmacological means for reducing the body's tendencies to develop arrhythmias as a result of stress.

Benefits of participating in this study include the opportunity to attend a classical music performance and learning about current research on heart-brain interaction and music cognition.

6. What are the possible disadvantages and risks of taking part?

There is a small risk that the music may be found to be unpleasant, but this is unlikely as the music consists of an attractive blend of many styles.

There is very little risk of you developing an abnormal heart rhythm while listening to the music. However you have an implanted pacemaker or ICD for the immediate correction of any such rhythm change in the unlikely event of such an occurrence.

The pacing during the concert may lead to mild shortness of breath or lightheadedness or palpitations but is unlikely to lead to any major adverse events. We can revert your pacemaker or ICD to the normal mode of pacing if you feel you cannot tolerate the pacing.

If you have private medical insurance you should seek approval from your insurer before agreeing to participate.

7. What will happen if I don't want to carry on with the study?

If you decide to take part you are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not influence your future medical care.

8. How will my information be kept confidential?

All information that is collected about you during the course of the research will be kept strictly confidential. Any information about you will have your name and address removed so that you cannot be recognised from it, and will be collected under a study number.

The data will be encrypted and stored securely on a hard drive that will be in a locked office. Only the study leads and researchers analysing the data will have access to the research data. Once analysis is completed, the study data will be deleted from the machine running the analysis.

The research data will be archived for 20 years according to Queen Mary University of London / Barts Health NHS Trust policy. The data will be archived in the Corporate Records Facility at 9 Prescot Street, London, E1 8PR.

9. What will happen to the results of this study?

The data you give will be analysed to determine patterns of heart electrical responses to different changes in the music.

The results will be published in peer-reviewed journals, conference proceedings, and other academic publications, and on the web and social media. It will also be disseminated through presentations at conferences and elsewhere.

If you wish we will inform you as to where you may obtain a copy of the publication(s).

10. Who is organising and funding this study?

This study is organised by Prof. Elaine Chew from the Centre for Digital Music at Queen Mary University of London (QMUL), and by Prof. Pier Lambiase and Prof. Peter Taggart from the Barts Heart Centre.

The study is funded in part by the QMUL Centre for Public Engagement.

11. Who has reviewed this study?

The Barts Heart Centre at St. Bartholomew's Hospital, and Oxford C Research Ethics Committee of the Health Research Authorities have reviewed this study.

12. Further information and contact details

If you have any questions about the study, please contact:

Professor Elaine Chew, Chief Investigator, elaine.chew@qmul.ac.uk
Professor Pier Lambiase, Principal Investigator, pier.lambiase@bartshealth.nhs.uk
Professor Peter Taggart, co-Principal Investigator, p.taggart@ucl.ac.uk

13. What if something goes wrong?

Queen Mary University of London has agreed that if you are harmed as a result of your participation in the study, you will be compensated, provided that, on the balance of probabilities, an injury was caused as a direct result of the intervention or procedures you received during the course of the study. These special compensation arrangements apply where an injury is caused to you that would not have occurred if you were not in the trial. These arrangements do not affect your right to pursue a claim through legal action.

End of the Participant Information Sheet

CONSENT FORM

Study Title (short): ***Cardiac response to live music performance***

Study Title (long): *Effect of Musical Changes and Transitions in Live Music Performance on Cardiac Electrophysiology as Quantified in Patients with Biventricular Pacemakers or ICDs*

Study Team: Prof. Elaine Chew, Prof. Pier Lambiase, Prof. Peter Taggart

Participant Number:

Please initial box

1. I confirm that I have read this Participant Information Sheet and Informed Consent Form (**Version 2.4, dated 23 April 2018**). I have had the opportunity to consider the information, ask questions, and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and that my decision will not affect my future care or legal rights. ☐

3. I give permission for photographs to be taken of me during the study for the purpose of publicising the research on the web, or in press releases or the media. I understand that the unlabelled photographs will be archived for 20 years with the research data. ☐

4. I understand that relevant sections of my medical notes and data collected during the study, may be looked at by individuals from Barts Heart Centre or Queen Mary University of London, from regulatory authorities or from the NHS Trust, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records. ☐

5. I understand that the information collected about me may be used to support other research in the future, and may be shared anonymously with other researchers, who may be outside of the UK and outside of the EU. ☐

6. Based on this information, I volunteer to take part in this study. ☐

Name of Participant	Date (dd-MON-yyyy)	Signature
Name of Person taking consent	Date (dd-MON-yyyy)	Signature

Please circle the most appropriate category:	**1 Completely Disagree**	**2 Strongly Disagree**	**3 Disagree**	**4 Neither Agree nor Disagree**	**5 Agree**	**6 Strongly Agree**	**7 Completely Agree**
1. I spend a lot of my free time doing music-related activities.	1	2	3	4	5	6	7
2. I sometimes choose music that can trigger shivers down my spine.	1	2	3	4	5	6	7
3. I enjoy writing about music, for example on blogs and forums.	1	2	3	4	5	6	7
4. If somebody starts singing a song I don't know, I can usually join in.	1	2	3	4	5	6	7
5. I am able to judge whether someone is a good singer or not.	1	2	3	4	5	6	7
6. I usually know when I'm hearing a song for the first time.	1	2	3	4	5	6	7
7. I can sing or play music from memory.	1	2	3	4	5	6	7
8. I'm intrigued by musical styles I'm not familiar with and want to find out more.	1	2	3	4	5	6	7
9. Pieces of music rarely evoke emotions for me.	1	2	3	4	5	6	7
10. I am able to hit the right notes when I sing along with a recording.	1	2	3	4	5	6	7

Please circle the most appropriate category:	**1 Completely Disagree**	**2 Strongly Disagree**	**3 Disagree**	**4 Neither Agree nor Disagree**	**5 Agree**	**6 Strongly Agree**	**7 Completely Agree**
11. I find it difficult to spot mistakes in a performance of a song even if I know the tune.	1	2	3	4	5	6	7
12. I can compare and discuss differences between two performances or versions of the same piece of music.	1	2	3	4	5	6	7
13. I have trouble recognizing a familiar song when played in a different way or by a different performer.	1	2	3	4	5	6	7
14. I have never been complimented for my talents as a musical performer.	1	2	3	4	5	6	7
15. I often read or search the internet for things related to music.	1	2	3	4	5	6	7
16. I often pick certain music to motivate or excite me.	1	2	3	4	5	6	7
17. I am not able to sing in harmony when somebody is singing a familiar tune.	1	2	3	4	5	6	7
18. I can tell when people sing or play out of time with the beat.	1	2	3	4	5	6	7
19. I am able to identify what is special about a given musical piece.	1	2	3	4	5	6	7
20. I am able to talk about the emotions that a piece of music evokes for me.	1	2	3	4	5	6	7

Please circle the most appropriate category:	1 Completely Disagree	2 Strongly Disagree	3 Disagree	4 Neither Agree nor Disagree	5 Agree	6 Strongly Agree	7 Completely Agree
21. I don't spend much of my disposable income on music.	1	2	3	4	5	6	7
22. I can tell when people sing or play out of tune.	1	2	3	4	5	6	7
23. When I sing, I have no idea whether I'm in tune or not.	1	2	3	4	5	6	7
24. Music is kind of an addiction for me - I couldn't live without it.	1	2	3	4	5	6	7
25. I don't like singing in public because I'm afraid that I would sing wrong notes.	1	2	3	4	5	6	7
26. When I hear a piece of music I can usually identify its genre.	1	2	3	4	5	6	7
27. I would not consider myself a musician.	1	2	3	4	5	6	7
28. I keep track of new music that I come across (e.g. new artists or recordings).	1	2	3	4	5	6	7
29. After hearing a new song two or three times, I can usually sing it by myself.	1	2	3	4	5	6	7
30. I only need to hear a new tune once and I can sing it back hours later.	1	2	3	4	5	6	7
31. Music can evoke my memories of past people and places.	1	2	3	4	5	6	7

Please circle the most appropriate category:

32. I engaged in regular, daily practice of a musical instrument (including voice) for **0 / 1 / 2 / 3 / 4-5 / 6-9 / 10 or more** years.
33. At the peak of my interest, I practiced **0 / 0.5 / 1 / 1.5 / 2 / 3-4 / 5 or more** hours per day on my primary instrument.
34. I have attended **0 / 1 / 2 / 3 / 4-6 / 7-10 / 11 or more** live music events as an audience member in the past twelve months.
35. I have had formal training in music theory for **0 / 0.5 / 1 / 2 / 3 / 4-6 / 7 or more** years.
36. I have had **0 / 0.5 / 1 / 2 / 3-5 / 6-9 / 10 or more** years of formal training on a musical instrument (including voice) during my lifetime.
37. I can play **0 / 1 / 2 / 3 / 4 / 5 / 6 or more** musical instruments.
38. I listen attentively to music for 0-15 min / 15-30 min / 30-60 min / 60-90 min / 2 hrs / 2-3 hrs / 4 hrs or more per day.
39. The instrument I play best (including voice) is ____

Please tick one of the following:
Occupational status

- ☐ Still at School
- ☐ At University
- ☐ In Full-time employment
- ☐ In Part-time employment
- ☐ Self-employed
- ☐ Homemaker/full time parent
- ☐ Unemployed
- ☐ Retired

What is the musical genre you mainly listen to?
(tick only one box)

- ☐ Rock/Pop
- ☐ Jazz
- ☐ Classical Music

What is the Highest educational qualification you have attained?

- ☐ Did not complete any school qualification
- ☐ Completed first school qualification at about 16 years (e.g. GCSE/Junior High School)
- ☐ Completed Second qualification (e.g A levels/ High School)
- ☐ Undergraduate degree or professional qualification
- ☐ Postgraduate degree
- ☐ I am still in education

If you are still in education, what is the highest qualification you expect to obtain?

- ☐ First school qualification (e.g. GCSE / Junior High School)
- ☐ Post-16 vocational course
- ☐ Second school qualification (e.g. A-levels / High School)
- ☐ Undergraduate degree or professional qualification
- ☐ Postgraduate degree
- ☐ Not applicable

C: Valence-Arousal Annotation Analysis

Participant 1:

Ballade No. 2, in F Major, Op. 38:

Event 1 (Excited): The Chopin begins just before this; most likely a transition from the Initial marking. Major key, tempo is steady in the triplet feel with no major fluctuations between beats (<1 BPM, which is likely imperceptible). A loudness change point occurred approximately 5 seconds prior, when the motif entered – this is likely a delayed response to this.

Event 2 (Happy): No major event – likely minor adjustment to refine feeling

Event 3 (Pleased): No major event – same as Event 2.

Event 4 (Agitated): This occurs at a 9 second delay from a major change point in the piece, where the motif fades away before the "storm" section dramatically begins. At this point, there is a loudness change point, followed by another 7 seconds later. The pulse is hard to follow, due to spacing in the running 16th notes in the treble, and distance between beats differs by ~30 BPM in the expression. The section is very unstable – this Event is likely a slightly delayed reaction to these features. Also, the bass line takes over from the treble voice just before the Event is marked in a very aggressive melody.

Event 5 (Surprised): Occurs just after the calm returns from the storm – there is a reduction in note density, with focus on the treble in a return to the major key, and there are less fluctuations in the pulse (~1 BPM).

Event 6 (Happy): Moving through expected chord structure to resolution, no changes to any other feature.

Event 7 (Surprised): Occurs just after unexpected resolution of the chord sequence and a loudness change point at the end of the rising phrase's climax.

Event 8 (Agitated): Lingering on a rolled chord, there is no resolution to the phrase through the lengthening of the pulse at its end.

Event 9 (Surprised): There is little key stability in the chord progression of the measures leading up to this Event, but pulse and loudness remain stable.

Event 10 (Agitated): Measures leading up to this feature an unstable rhythm, with rolling lines in both treble and bass and no clear indication of the beat or key. The composition here intends the piece to feel like it has fallen apart.

Event 11 (Pleased): The final storm recedes and the piece finally resolves. It does not end on the major tone of the initial motif, but the motif's rhythm returns for a long rubato. The release is very savored by the pianist, with a pulse of ~25 BPM.

Event 12 (Pleased): Continuation of Event 11 adjustment

VT before during after (Holst):

Event 13 (Surprised): No event – occurs between Chopin and Mars.

Event 14 (Nervous): Well into Mars at this time - there is a slow chromatic buildup (no strong sense of key) to this Event, which occurs just after the rhythms from the ventricular tachycardia are introduced in the bass, removing all sense of pulse.

Event 15 (Nervous): Continuation of Event 14 adjustment. Event 16 (Agitated): There is a strong loud-to-soft drop (loudness change point), with a loss of pulse at the phrase-end rubato (huge change from ~158 to ~38 BPM in the heart rate pulse. The bass takes over also with staccato note repetition.

Event 17 (Surprised): The same dissonant chord is repeated multiple times with sparse voicing to the end of the piece.

Participant 2:

Ballade No. 2, in F Major, Op. 38:

Event 1 (Pleased): In the same intro section of Chopin as Participant 1's first Event. Stable section with expected melody/harmony interaction and consistent pacing.

Event 2 (Happy): Still in the intro section, there is a loudness change point as the performer brings forth a slight violation of the chord structure with only a slight delay in the resolution, which is satisfying because of the proximity of notes in the resolution.

Event 3 (Surprised): Fading out of the intro, this occurs around the period where the bass voice becomes more prominent in the melody. There is a loudness change when this occurs.

Event 4 (Bored): Start of the storm – close to Participant 1's Event 4.

Event 5 (Sad): This period of time goes through the growth and peak of the storm, with clustering of rolling notes in the treble and prominence in the bass transitioning to a steady pulse of chords. The chord structure moves chromatically to a peak where there is a prominent loudness change before the storm fades.

Event 6 (Pleased): The same triplet motif in major feel has returned and continues through this section.

Event 7 (Anxious): There is an inkling of a transition here with a slowly rising tempo and loudness through the progression.

Event 8 (Surprised): There is a strong violation of the chord structure at the end of the phrase just before this Event, followed by a loudness change at a prominent tenor note, and loudness continues to increase just before the storm returns.

Event 9 (Pleased): This storm is in a major tone, but loudness increases throughout the section. There is a slight pause in the pulse at the peak of the storm where the performer highlights a slight deviation and resolution in the chord structure.

Event 10 (Content): After a rolling note, the triplet feel begins again and the piece returns to a sense of normalcy with a reduction in tempo (from ~72 to ~28 BPM).

Event 11 (Pleased): Violations of expectation in the melody, which is passed between treble and bass. Pulse slows from ~62 to ~32 BPM in this section.

Event 12 (Content): No major change from Event 11.

Event 13 (Pleased): Return of the triplet motif in the bass voice.

Event 14 (Content): The storm returns in the same transition voicing of the original storm. There is a strong harmonic violation at this sudden Event.

Event 15 (Content): A different harmonic violation is introduced to the storm from its first rendition, accompanied by a slow in the pulse to highlight the chord and resolution before proceeding in a harmonic structure with no expected progressions, up to the return of the original storm.

Event 16 (Content): The original storm as heard from Event 4 returns.

Event 17 (Sad): The storm progresses as before with loose pulse (fluctuation between ~118 and ~125 BPM) before taking a different, yet still unexpected violation of the chord structure in a transition to a bass line feature.

Event 18 (Calm): The bass line takes over, seeming to plod with a slowing pulse through the section chromatically before the treble comes back into the foreground. There is a large distance between the two voices with no clear harmonic structure.

Event 19 (Surprised): The triplets return quietly in minor feel with slow pulse in the same section of the piece as Participant 1's Event 11.

Event 20 (Nervous): Just after Chopin ends on a minor resolution.

VT before during after (Holst):

Event 21 (Pleased): No event – occurs between Chopin and Mars.

Event 22 (Neutral): Same as Event 22 (possible reflection on the previous piece).
Event 23 (Disgusted): Both lines play wide octaves in staccato fashion with introduction of some arrhythmia pulse (reaching a peak at ~328 BPM just before this Event begins). Through this plateau, there are multiple pulse and harmonic violations, with sections of soft and loud dynamic buildups, but there is no resolution through the section.
Event 24 (Calm): There is a large loud-to-soft drop before the bass takes over prominence in unison with treble in soft dissonance clusters above. There is no clear harmonic structure and the pulse stays constant with the staccato bass.
Event 25 (Content): Both voices play the same dissonant chord in repetition and consistent pulse, which increases in loudness to the end of the piece with no resolution.

VT before after UNI (Chopin)
Event 26 (Neutral): No event – occurs between Mars and *VT before after UNI*.
Event 27 (Pleased): Same familiar chord and melodic structure as the original heard earlier, with several large rhythmic violations from the arrhythmias (jumping from as much as ~44 to ~226 BPM in some places).
Event 28 (Surprised): Same idea as Event 27, with more constant rhythmic violations. There is no sense of pulse in this section.
Event 29 (Anxious): This is where the ventricular tachycardia begins (reaching ~327 BPM at the highest peak), in conjunction with sudden increased loudness and harmonic instability in the storm section. There is no stability in any part of the section.
Event 30 (Frustrated): The VT continues with a prominent chromatic line in the bass.
Event 31 (Relaxed): A very quick transition jumping from ~230 BPM to ~62 BPM in the VT is followed by a more stable tempo around ~79 BPM for the rest of the section.
Event 32 (Content): The long transition through the rolling treble melody closes and is followed by the return to the main motif at a relatively stable tempo (some small jumps between ~50 and ~80 BPM)
Event 33 (Content): Unexpected harmonic violation composed here, tempo remains consistent between 4 beats without any VT.
Event 34 (Pleased): No changes from Event 34.
Event 35 (Pleased): Slight loudness increase, otherwise same as Events 33 and 34.
Event 36 (Surprised): Large loudness change, increase back into chromatic storm with consistent pulse.
Event 37 (Surprised): Tachycardia gives a percussive interjection to the consistency.
Event 38 (Neutral): Consistent rhythmic chromatic transition with bass prominence.
Event 39 (Calm): The storm reaches its peak and descends chromatically over a stable rhythm, getting softer with each beat.
Event 40 (Frustrated): No major change from Event 39, transition continues.
Event 41 (Content): Piece resolves on a major chord following a brief reintroduction of the triplet theme.
Event 42 (Neutral): No event – performance has concluded.

Participant 3:

Ballade No. 2, in F Major, Op. 38:
Event 1 (Neutral): No events - prior to the beginning of the piece.
Event 2 (Neutral): Stable section with expected melody/harmony interaction and consistent pacing, triplets introduced.
Event 3 (Nervous): Same motif, stable tempo with a loudness change point.
Event 4 (Pleased): Same motif, stable tempo with a loudness change point.
Event 5 (Happy): Loudness change point as the performer brings out a weak violation of the chord structure.
Event 6 (Surprised): Rubato as the performer highlights another violation of the chord structure at the end of the phrase.
Event 7 (Surprised): Violation resolved, triplets continue on.
Event 8 (Nervous): Loudness change point followed by deviation from the chord progression in the treble line, which takes the piece to a minor feel.
Event 9 (Agitated): Start of the storm section – sudden increase in loudness with unstable pulse fluctuations.
Event 10 (Agitated): Violation of expected melodic line and harmonic structure as the bass takes over with rubato delaying the reentering of running 16^{th} notes in the treble. This Event continues through the storm section.
Event 11 (Frustrated): Chromatic movement in the treble with bass rolling underneath and decrease in volume.
Event 12 (Disgusted): Rolling 16^{th} notes in treble melody, decrease in tempo and loudness as the transition returns the melody to the main mode of the piece.
Event 13 (Anxious): Return to the triplet feel.
Event 14 (Surprised): Triplets slow from pulse of ~52 to ~29 BPM.
Event 15 (Nervous): Triplets reenter after long pause in a minor feel, with loudness increases steadily, hinting at a transition.
Event 16 (Nervous): The chromatic transition into the storm section reappears in a major tone, but loudness increases throughout the section. There is a slight pause in the pulse at the peak of the storm where the performer highlights a slight deviation and resolution in the chord structure.
Event 17 (Frustrated): Storm section ends unresolved on a rolling chord.
Event 18 (Disgusted): Same as Participant 2's Event 11. Violations of expectation in the melody, which is passed between treble and bass, occur while pulse slows from ~62 to ~32 BPM in this section.
Event 19 (Frustrated): Prominent tenor voice, while loudness increases steadily and the sense of chord progression disappears as it moves back into the same chromatic transition into the storm section.
Event 20 (Surprised): Same as Participant 2 Event 15 - A different harmonic violation is introduced to the storm from its first rendition, accompanied by a slow in the pulse to highlight the chord and resolution before proceeding in a harmonic structure with no expected progressions to the return of the original storm.
Event 21 (Frustrated): Same as Participant 2 Event 17 - The storm progresses as before with loose pulse (fluctuation between ~118 and ~125 BPM) before taking a different, yet still unexpected violation of the chord structure in a transition to a bass line feature. This continues to just before the end of the final storm.
Event 22 (Agitated): Bass and treble take turns in rising lines as the chromaticism in the chord structure rises to the climax with a ringing treble note (bell tone).
Event 23 (Anxious): The triplets return with dramatic reduction in loudness in minor feel, hanging onto a leading tone (holding the 4^{th} in rubato reflecting at a pulse of 25 BPM).
Event 24 (Surprised): The resolution from the leading tone to the minor of the key is delayed by rearticulating the notes of the chord individually before finally settling after a long expressive pause (~22 BPM).

VT before during after (Holst):
Event 25 (Neutral): No event – return to stasis following the end of Chopin.
Event 26 (Pleased): Steady pulse with minor interruptions by the arrhythmias. There are no major dissonances with the voicing being sparse, but no clear harmonic progression.
Event 27 (Pleased): Bass line becomes prominent, voicing still sparse and rhythm stable for 8 beats around this Event.

Event 28 (Bored): Continues from Event 27, with more rhythmic interruptions, bass and treble voices play in octave unison.
Event 29 (Content): Ventricular tachycardia rhythms begin.
Event 30 (Relaxed): VT continues into stable pulse with bass chords, treble plays at high melodic distance from the underlying chords and is loud and prominent.
Event 31 (Content): No major change from Event 30.
Event 32 (Sad): Pulse slows from ~181 to ~72 BPM during a rubato at the decrease transition in the loudness, where both voices join in a dotted feel interrupted by VT rhythms accented with octaves in the treble.
Event 33 (Content): Stable rhythm returns with chromatic ascensions in the treble.
Event 34 (Relaxed): Treble lead continues, loudness increases slightly.
Event 35 (Relaxed): No major change from Event 35.
Event 36 (Relaxed): Chromaticism continues at steady pulse with large loudness change as aggressive bass line covers the treble voice.
Event 37 (Pleased): Same as Participant 2 Event 24 - There is a large loud-to-soft drop before the bass takes over prominence in unison with treble in soft dissonance clusters above. There is no clear harmonic structure and the pulse stays constant with the staccato bass.
Event 38 (Bored): No major change from Event 37.
Event 39 (Relaxed): No major change from Event 38.
Event 40 (Relaxed): No major change from Event 39.
Event 41 (Relaxed): Loudness increase to steady pulse with treble and bass in unison.
Event 42 (Calm): Chord settles on dissonance; after one last arrhythmia interruption (spike to 314 BPM between beats) and continues to the end of the piece.

VT before after UNI (Chopin):
Event 43 (Neutral): No event – return to stasis following the end of Holst.
Event 44 (Anxious): Same as Participant 2's Event 27 – Rhythmic instability begins with the arrhythmias, while the familiar motif has chord violations from the expected and original progression. There are several large rhythmic violations from the arrhythmias (jumping from as much as ~44 to ~226 BPM in some places). This continues through the end of the first storm.
Event 45 (Anxious): The long transition (28 BPM) at the end of the storm closes with resolution to the diatonic root.
Event 46 (Anxious): Same as Participant 2's Event 33 – Unexpected harmonic violation composed here, tempo remains consistent between 4 beats without any VT.
Event 47 (Pleased): Loudness increases suddenly to regular chromatic chord progression and stable pulse.
Event 48 (Pleased): No major change from Event 47.
Event 49 (Content): No major change from Event 48 – progression continues with rolling bass underneath.
Event 50 (Content): Triplet theme returns with arrhythmia influence, slight minor feel.
Event 51 (Content): Rhythmic interjection (peak of 259 BPM in the arrhythmia) to the motif.
Event 52 (Happy): Rhythmic chordal progression, rising chromatically with stable pulse in transition to the next storm event.
Event 53 (Content): The storm returns with stable pulse in the treble and rolling bass line underneath. The pulse slows dramatically at the end of the phrase before the triplets return softly and resolve to the major.
Event 54 (Pleased): The major resolution decays to the end of the performance.
Event 55 (Surprised): No major change – end of performance.
Event 56 (Neutral): No major change – end of performance.

Appendix D
Tension Annotation Analysis

Events occurring during periods of silence or those ignored as being insignificant (change of < 5 points from the previous notable Event) are noted and indicated with a ~~strikethrough.~~

Patient 1:

Ballade No. 2, in F Major, Op. 38:
Event 1 (Decrease): During the middle of the first storm - there is one loudness peak just as the treble reaches the highest pitch of its 16th note runs.
Event 2 (Decrease): Just after the loudness change when the treble takes over into the transition back into the triplet motif.

Patient 2:

Ballade No. 2, in F Major, Op. 38:
~~Event 1 (Increase): No major event – music has not begun yet.~~
Event 2 (Increase): Triplets under way, no major changes in tempo or loudness, other than slight accenting on the beats to give a lilted feeling.
Event 3 (Decrease): No major event – triplets continue.
~~Event 4 (Decrease): Event ignored – change of only 2 points from Event 3.~~
Event 5 (Increase): Triplets slow from ~45 to ~16 BPM to fade out.
Event 6 (Increase): Storm section has begun, loudness and tempo increase.
Event 7 (Decrease): Rhythmic feel returns to regular pulse now that the running lines have stopped.
Event 8 (Decrease): Storm section fades out with loudness decrease, rhythm regular with less dissonance.
~~Event 9 (Increase): Event ignored – change of only 3 points from Event 8.~~
~~Event 10 (Decrease): Event ignored – change of only 2 point from Event 8.~~
Event 11 (Increase): Harmonic violation at the inkling of a transition with slight loudness increase as the performer accents the chord.
Event 12 (Increase): Slight dissonances and deviation from the familiar chord progression of the section with small rubato to highlight the changes (~68 to ~48 BPM).
Event 13 (Decrease): Loudness change point into the storm section with increased tempo.
Event 14 (Increase): Prominent tenor note with a loudness change point, followed by slight violations to the harmonic structure.
Event 15 (Increase): Transition back into the storm section, dissonance in the melody line as the loudness increases following a change point.
Event 16 (Increase): The storm with 16th note runs returns and change to loudness.
Event 17 (Increase): Different harmonic violations from the first storm with prominent and aggressive bass voice.
Event 18 (Decrease): Chromatic rising line with increasing tempo. There are no changes to the end of the piece.

VT before during after (Holst):
~~Event 19 (Increase): No major event – silence between Chopin and Holst.~~
~~Event 20 (Increase): Event ignored – change of only 1 point from Event 19.~~
Event 21 (Increase): Mars has begun and bass and treble dissonance begins.
~~Event 22 (Decrease): Event ignored – change of only 1 point from Event 21.~~
Event 23 (Increase): Loudness begins to increase, continued dissonance with introduction of rhythms from the arrhythmias.
Event 24 (Increase): Strong rhythmic interruption from arrhythmias (reaching ~327 BPM between pulses), unclear harmonic structure.
~~Event 25 (Increase): Event ignored – change of only 1 point from Event 25.~~
Event 26 (Decrease): Large distance with increased loudness between treble and bass voices but no dissonance, arrhythmias continue.
Event 27 (Increase): Arrhythmias reach highest pulse between beats (~490 in a skipping heart rhythm) before dramatic loudness reduction and return to stable rhythm with rising chromatic treble lines and increasing loudness.
Event 28 (Decrease): Unison voices increase in loudness (to Sone value of 0.85).
Event 29 (Increase): Chromatic bass line with dissonant chords in treble.
Event 30 (Decrease): Repeated dissonance with sparse voicing. Continues to the end of the piece.

VT before after UNI (Chopin):
~~Event 31 (Decrease): Event ignored – silence between Arrhythmia Suite pieces.~~
~~Event 32 (Decrease): Event ignored – change of only 1 point from Event 31.~~
Event 33 (Increase): Loudness change point as arrhythmias are introduced to Chopin triplets.
Event 34 (Increase): Arrhythmias increase, jumping in ranges such as ~81 to ~220 to ~124 BPM in the span of 3 pulses.
Event 35 (Increase): Stable pulse for 5 beats with a slow in pulse at the end of the phrase before more arrhythmias bring the pulse back to ~222 BPM in some spots.
Event 36 (Increase): Storm section with very inconsistent pulse.
Event 37 (Decrease): Rubato slowing the phrase end to ~102 and then a quick transition back to ~230 BPM.
Event 38 (Decrease): Pulse consistent, treble chords with bass rolling 16th note features underneath.
~~Event 39 (Decrease): Event ignored – change of only 1 point from Event 38.~~
Event 40 (Increase): Long transition closes, only minor rhythmic interruptions.
Event 41 (Decrease): Quick two-chord transition with unexpected harmonic change back into the storm section.
Event 42 (Increase): Storm progression with stable tempo.
Event 43 (Increase): Slowing at phrase end to ~54 BPM is quickly interrupted by arrhythmia, putting the beat around ~114 BPM.
Event 44 (Increase): Percussive interjections in stable rhythmic line.
Event 45 (Decrease): Storm section builds with stable rhythm.
Event 46 (Decrease): Storm continues – this tension rating is stable through the end/resolution of the piece.

Patient 3:

Ballade No. 2, in F Major, Op. 38:
~~Event 1 (Decrease): No major event – music has not begun yet.~~
Event 2 (Decrease): Triplets begin softly.
~~Event 3 (Decrease): Event ignored – change of only 1 point from Event 2.~~
~~Event 4 (Increase): Event ignored – change of only 3 points from Event 2.~~
~~Event 5 (Decrease): Event ignored – change of only 2 points from Event 2. These four points appear to be a minor readjustment with the triplet motif.~~
Event 6 (Increase): Prominent leading tones in the bass line, tempo slows to the end of the phrase, ~54 to ~21 BPM.
Event 7 (Increase): End of the phrase, resolved chord with each note articulated.
Event 8 (Increase): Resolved chord fades to silence.
Event 9 (Increase): Storm begins, loudness increases with tempo and loss of harmonic progression in the 16th note features.
Event 10 (Decrease): Rhythm becomes consistent again with a resolution in the harmonic structure and treble melody just before the marked change.

Event 11 (Decrease): Stable rhythm, loudness decreases with return to recognizable chord progression.
Event 12 (Increase): Prominent tenor voice takes over in the melody building in the transition back to the storm.
Event 13 (Decrease): Chromatic rise to the storm in a major feel.
Event 14 (Decrease): Storm fades away with some chromatic melody lines with unexpected resolutions before the triplet feel returns for two measures.
Event 15 (Increase): Tenor voice takes over with loudness increasing and some violations of the melodic line's movement.
Event 16 (Increase): Tempo and loudness increase in the chromatic transition back into the storm section.
~~Event 17 (Decrease): Event ignored – change of only 3 points from Event 16.~~
Event 18 (Increase): Bass line takes over melody in transition within the storm.
~~Event 19 (Increase): Event ignored – change of only 3 points from Event 18.~~
Event 20 (Increase): Storm section reaches its peak with accented descending line in the bass and great distance between the voices.
~~Event 21 (Decrease): Event ignored – change of only 2 points from Event 20.~~
~~Event 22 (Increase): Event ignored – change of only 3 points from Event 20.~~
Event 23 (Increase): Loudness change points in fluctuations from accented notes, no clear harmonic structure with bass still descending and high treble above.
Event 24 (Increase): Chromatic ascension in bass grows steadily louder.
Event 25 (Decrease): Storm section ends and fades away.
Event 26 (Decrease): Triplets return and resolve to the minor.

VT before during after (Holst):
~~Event 27 (Increase): No major event – silence between Chopin and Holst.~~
~~Event 28 (Increase): Event ignored – change of only 3 points from Event 27.~~
Event 29 (Increase): Treble and bass play in dissonance with some interruptions from arrhythmias.
Event 30 (Increase): Less dissonance but no clear harmonic progression, more arrhythmia interruptions.
Event 31 (Increase): Octave unisons between spread voices, ascending line with increasing loudness.
Event 32 (Increase): Ventricular tachycardia begins, tempo reaches ~237 BPM.
Event 33 (Decrease): Transition back into rhythmic stability with chromatic ascending treble melody.
~~Event 34 (Increase): Event ignored – change of only 1 point from Event 33.~~
Event 35 (Decrease): Stable rhythm, treble line plays in mostly chromatic ascension.
~~Event 36 (Increase): Event ignored – change of only 4 points from Event 35.~~
Event 37 (Increase): Dramatic loud-to-soft drop with bass in melody and treble in
dissonant chords overhead.
~~Event 38 (Increase): Event ignored – change of only 3 points from Event 37.~~
~~Event 39 (Increase): Event ignored – change of only 4 points from Event 37.~~
Event 40 (Increase): Chromatic movement continues in bass, loudness increases on accented notes.
~~Event 41 (Increase): Event ignored – change of only 3 points from Event 40.~~
Event 42 (Increase): Harmonic violation.
Event 43 (Increase): Repetition of same dissonant chord in treble voices.
Event 44 (Increase): Dissonant chord repeated with addition of more dissonances in bass voices and increasing loudness before piece ends without resolution.

VT before after UNI (Chopin):
~~Event 45 (Decrease): No major event – silence between Arrhythmia Suite pieces.~~
~~Event 46 (Increase): No major event - silence between Arrhythmia Suite pieces.~~
Event 47 (Increase): Introduction of arrhythmia gives dramatic peak in the pulse just before the marker (from ~86 to ~230 BPM).
~~Event 48 (Increase): Event ignored – change of only 1 point from Event 47.~~
Event 49 (Decrease): Long transition closes and triplets reenter.
Event 50 (Decrease): Final storm ends, triplets reenter with reduction in loudness.

Appendix E

Change Point and Transition Annotation Analysis

Patient 1:

Ballade No. 2, in F Major, Op. 38:
Sudden Change (Measure 34): Occurs around the unexpected harmonic progression in the triplet section.
Sudden Change (Measure 47): Start of the first storm section.
Transition (Measures 79 – 96): Transition out of the first storm section, goes all the way through the triplet motif until the bass line prominence at an unexpected resolution and dissonance in a the first beat.
Sudden Change (Measures 108 –111): Chromatic transition goes back into the storm.
Sudden Change (Measures 130 – 134): Chromatic transition goes back into the storm (but the marked change ends before the chromatic line finishes).
Sudden Change (Measure 137): Chromatic rising voices in the bass with lots of dissonance.

VT before after UNI (Chopin):
Sudden Change (Measure 59): 5/8 *a tempo* measure of unexpected harmonic violation by two loud dissonant chords.
Sudden Change (Measure 74 – 76): Triplets in minor feel followed by dissonance and increased loudness from now prominent bass line.
Transition (Measure 96): Last bar of chromatic dissonance before the triplets return at the end of the piece.

Patient 2:

Ballade No. 2, in F Major, Op. 38:
Transition (Measure 12): No major musical event – consistent in the triplets.
Sudden Changes (Measure 19): Leading tone coming out of melodic dissonance.
Transition (Measures 35 -38): Triplets in minor feel up to bass line prominence on melodic dissonance.
Sudden Change (Measure 38): Bass line melodic dissonance.
Transitions (Measures 44 – 46): The *smorsando*, end of the phrase to the resolution.
Transition (Measure 46): Articulation of the notes in the resolved chord just before the storm.
Transition (Measures 66 – 88): Starts at the middle of the storm, goes to the end of the first *a tempo* phrase with the fermata breath at the end.
Sudden Change (Measure 93): Arpeggiated chord, not dissonant.
Sudden Change (Measure 108): Melodic line resolves unexpectedly before going back into the chromatic ascension before the storm.
Sudden Change (Measure 116): First triplets in the next *a tempo* section.
Sudden Change (Measure 132): Transition of chromatic progression of chords begins into the storm again.
Transitions (Measures 173 – 175): No major musical event – perhaps reaction to increased distance between treble and bass voices.

VT before during after (Holst):
Sudden Change (Measure 1): Mars begins.
Transitions (Measures 4-8): Treble voice enters, staccato and syncopated dissonant chords in final measure.
Transitions (Measures 13 – 22): Long transition into marked Letter C, starts with introduction of triplet features before chromatic chord progressions end.
Sudden Change (Measure 43): At the start of marked Letter E, dynamic change to *p* with ascending chromatic chords in the treble.
Transition (Measures 51 – 54): Chromatic chord progression into and through first measure of marked Letter F, loudness increases through this section.
Sudden Change (Measure 62): Staccato chords begin at the 5/4 measure.
Transition (Measures 62 – 67): Unison staccato voices repeat a dissonant chord to the end of the piece.

VT before after UNI (Chopin):
Sudden Change (Measure 1): Chopin begins.
Transition (Measures 4 – 30): The entire first section of the piece, featuring the triplet motif through the arpeggiated chord before the storm.
Transitions (Measures 50 – 55): Rolling 16th note treble melody through the first measure of marked Letter H, where the *a tempo* returns.
Sudden Change (Measure 59): Sudden 5/8 *a tempo* measure of unexpected harmonic violation by two loud dissonant chords.
Sudden Change (Measure 73): Change to 6/8 with familiar *a tempo* dotted rhythm.
Sudden Change (Measure 76): Jump to *f* with bass line taking over dotted rhythm in a 3/4 measure.
Sudden Change (Measure 97): Quick dynamic reduction to *pp* with motif entering.

Patient 3:

Ballade No. 2, in F Major, Op. 38:
Sudden Change (Measure 47): Start of the first storm section.
Transition (Measures 72 – 79): Treble plays the beats in descending line out of the storm.
Transition (Measures 83 – 88): Return to the triplet theme, which slows to a fermata pause.
Transition (Measures 100 – 109): Variation on triplet theme progresses to the start of the storm transition.
Sudden Change (Measure 115): *Sforzando* while the treble hangs onto a chord with unexpected resolution.
Transitions (Measures 134 – 164): Chromatic chord progression back into the storm section and through the 16th note features and bass assumption of the melody.
Transitions (Measures 168 – 169): Final measure of bass melody before the *Agitato* section begins.
Sudden Change (Measure 197): Ringing *fff* dissonant chord at the end of the storm.
Sudden Change (Measure 197): Triplets reenter after the fermata.

VT before during after (Holst):
Sudden Change (Measure 1): Mars begins.
Transitions (Measures 21 – 32): Bass and treble play unison in dissonance through the first phrase of marked Letter C until the treble distance ends and 5/8 resumes.
Sudden Change (Measure 42): Crescendo held on dissonant voices in treble through the end of marked Letter D.
Transition (Measures 51 – 52): Chromatic ascension in dissonant chords with *molto cresc.* through the end of marked section E where the loudness and tempo drop.
Sudden Change (Measure 65): Final dissonant chord of the piece.

VT before after UNI (Chopin):
Transitions (Measures 40 – 53): Dissonant chords in the treble descend through marked Letter G and ascending treble melody takes over with pulse in the bass to the end of the section where the motif returns.
Sudden Change (Measure 60): Letter I, dynamic increase to f with treble chords descending over rolling bass feature.
Transition (Measures 68 – 75): Treble takes over 16th note figures and returns to *a tempo* with a variation on the triplet figure with *f* change 1 measure before Letter K.
Sudden Change (Measure 75): Bass line comes forward in dynamic increase.
Transition (Measures 94 – 96): End of the final storm section, treble pulse descends to a release before a rest at the end of the phrase.
Sudden Change (Measure 99): Major resolution of the piece in the final chord.

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