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When Hearts Beat as One – Cardiac Dynamics and Synchrony in String Quartet Performances

A thesis submitted for the degree of
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Abstract

This master's thesis examines the musicians' cardiac rhythms in string quartet performances. It attempts to capture and demonstrate the cardiac dynamics and synchrony in musical ensembles by analyzing two cases, including a student string quartet (the Borealis String Quartet) and a world-renowned quartet (the Danish String Quartet) performing in different experimental configurations. Two string quartets measured resting heart rate as the Quiet Baseline and repeated Joseph Haydn's *String Quartet in B-flat major* in conditions that differ in communication constraints such as the Blind, Violin-isolated, Score-directed, Normal, and Concert. Besides, the Danish String Quartet performed an additional Moving Baseline condition in which they played a scale together, as well as a Sight-reading condition involving a music excerpt they had never heard or practiced before. Unlike most previous studies on music and physiological responses, this study employs both linear and nonlinear methods to reveal different aspects of cardiac dynamics from the individual to the group level. Firstly, we observed more predictable individuals' cardiac dynamics during the musical performance than the resting baseline in both quartets. Secondly, group-level synchrony analysis demonstrated that both quartets' cardiac synchrony levels increased during performance conditions relative to the Quiet Baseline. Moreover, the cardiac synchrony level of the Borealis String Quartet was affected to varying degrees by adverse conditions. However, the Danish String Quartet, as an expert group, was more resistant to constraints. Finally, we compared the cardiac synchrony level of the two quartets in identical pairwise conditions. We found the Danish String Quartet has a higher cardiac coupling rate relative to the Borealis String Quartet. Overall, our findings suggest that performing in the string quartet facilitates more predictable cardiac dynamics and synchrony. Different constraints may affect cardiac synchrony to the degree associated with the level of expertise.

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Wenbo Yi 易闻波

Contents

Chapter 1

Introduction

1.1 Motivation

For more than a decade, I have been fascinated by how music subtly affects people's behavior and emotions. As a former pianist and audio engineer, having served as both performer and producer, I have always strived to understand how we can better share experiences and convey emotions through music. During my two-year study in the Music, Communication and Technology Master's program at the University of Oslo, by taking courses such as Music Psychology, Music-related Motion Tracking, Music and Machine Learning, Vision and Brain, as well as the training in the RITMO Center for Interdisciplinary Studies in Time, Rhythm, and Motion as a research assistant, I was introduced to music cognition, scientific computing, and various techniques to capture and analyze the physical and physiological data of human. All these experiences strongly motivated me to refine and facilitate my interests in discovering how music influences us and how we are connected by music as the core of my Master's research.

The widespread notion that music is a rewarding and motivating activity to facilitate joint action, synchronize individuals, and develop social bonding for a group of people (Chanda, 2013; Dunbar, 2012; Kogan, 1997; Malloch & Trevarthen, 2009), which can be used as a tool of pleasure and soothing throughout human evolution (Wright et al., 2022). With the development of embodied cognition theory, researchers have started to focus on how the human body functions as a mediator for music cognitive processing, thereby establishing feelings and concepts in psychophysiological and sensory-motor systems (Leman, 2008; Leman & Maes, 2014). A wide range of studies has investigated sensorimotor synchronization (e.g., Goebl & Palmer, 2009; Palmer et al., 2019; Phillips-Silver & Keller, 2012; Phillips-Silver & Trainor, 2005, 2007; Van Der Steen & Keller, 2013) and neural entrainment (e.g., Large, 2010; Large et al., 2015; Nozaradan et al., 2012, 2015; Stupacher et al., 2017; Tierney & Kraus, 2015) in musical ensembles. These studies have extensively revealed how individuals physically coordinate their actions with music rhythm and collaborators and how the brain waves synchronize to the periodic stimuli. However, how the temporal coordination of human behaviors affects physiological rhythms still remains largely unknown, especially regarding the mechanisms of the autonomic nervous system influenced by music activities, as the visceral responses are one of the critical components of emotional state and social communication (Scherer, 2005; Shaffer et al., 2014). Thus, it is necessary to accumulate more physiological data and investigate the physiological nature of interpersonal synchrony in musical ensembles.

Fortunately, the motivation for my master's thesis coincided with the MusicLab Copenhagen project[1] and the MusicTestLab project[2] at the University of Oslo's RITMO Centre for Interdisciplinary Studies in Time, Rhythm, and Motion. The main objective of the MusicLab Copenhagen project was to understand how musicians' and audiences' minds and bodies are engaged and share experiences in music activity, through a special "science concert" held by RITMO and one of the world's best chamber ensembles, the Danish String Quartet (DSQ) in Copenhagen Concert Hall. In collaboration with a team of researchers from the University of Oslo and several other European institutions, the event combined the expertise ranging from musicology, music technology, and experimental psychology, applied electrocardiogram (EKG), pupillometry, and motion capture to measure the physical and physiological responses of four musicians and selected audience members. In addition, the MusicTestLab project was the pilot project of MusicLab Copenhagen, held before the actual concert at the University of Oslo with the Borealis String Quartet - a student string quartet from the Norwegian Academy of Music (NMH). Researchers implemented a similar setup in a public space and tested the feasibility of experimental equipment and designs in a real-world scenario. Therefore, the MusicLab Copenhagen and the MusicTestLab provided me with an excellent opportunity to collect physiological data from two string quartets and contribute to exploring musicians' physiological responses and mechanisms in musical ensembles.

1.2 Research Questions and Hypotheses

The primary research objective of this thesis is to investigate the physiological rhythm, more specifically, musicians' cardiac dynamics in string quartet performances in different experimental conditions with varying constraints by applying linear and nonlinear analysis methods[3]. From this, the three research questions emerged as follows:

[1] See https://www.uio.no/ritmo/english/projects/musiclab/2021/dsq/
[2] See https://www.uio.no/ritmo/english/projects/musiclab/2020/musictestlab/index.html
[3] The details of the research background, experimental design, and data analysis methods will be elaborated in the following sections.

Research Question 1: How do the cardiac dynamics change during the musical performance in different experimental conditions?

As in many other biological systems, nonlinearities exist in cardiac activity on multiple biological scales: subcellular (e.g., at the single-channel level), cellular, and whole-organ (Krogh-Madsen & Christini, 2012). Despite the nonlinear nature of cardiac rhythm, limited studies have applied nonlinear techniques to capture the dynamics of the cardiovascular system during rhythmic musical behaviors (Wright et al., 2022; Wright & Palmer, 2020). Therefore, in the present study, except for the conventional linear measurement of the cardiac activity, such as heart rate and heart rate variability. We introduced a novel nonlinear method - Recurrence Quantification Analysis (RQA) to analyze the nonlinear dynamics of individuals' cardiac rhythms, and provide a more comprehensive perspective on the variations of cardiac dynamics during musical performances. Based on the previous empirical evidence (de Manzano et al., 2010; Nakahara et al., 2011; Wright & Palmer, 2020), we expect that musicians will have a higher heart rate and a lower heart rate variability during the musical performance compared to the quiet baseline, and adverse performance conditions compared to normal conditions. Moreover, we also hypothesize that more predictable cardiac dynamics will coincide with musical performance relative to the stationary baseline, and normal performance conditions versus adverse conditions.

Research Question 2: What is the relationship of cardiac dynamics between the collaborators of the string quartet? Does synchronization occur when they perform together?

Music has a consistent and similar influence on the autonomic nervous system (L. Bernardi et al., 2006, 2009; N. F. Bernardi et al., 2017): in general, music rhythm and loudness level can similarly influence heart rate, with the degree of the effect being related to resting heart rate (Bretherton et al., 2019; Gomez & Danuser, 2007; Kölsch & Jäncke, 2015; van Dyck et al., 2017). In addition, researchers also found that when individuals listen or sing together, the synchronization of cardiac and respiratory rhythms shows a modest but solid increase compared with baseline (N. F. Bernardi et al., 2017; Müller & Lindenberger, 2011). As far as we know, no empirical studies have examined the phenomenon of physiological synchronization in instrumental ensembles. Hence, we applied a nonlinear multivariate correlation technique - Multidimensional Recurrence Quantification Analysis (MdRQA) to quantify the group-level cardiac synchrony among the four musicians in the string quartet.

We predict that the cardiac activity will have higher coupling levels during musical performances and normal experimental conditions relative to the quiet baseline and adverse conditions.

> **Research Question 3:** What is the difference between the cardiac dynamics of the Danish String Quartet and the Borealis String Quartet?

Playing musical instruments is an extremely complex task that demands a lot of practice over a long period. Musical performance not only requires musicians to retrieve musical information from long-term memory and manage their subsequent performance in the working memory system, but also needs performers to precisely handle their complex movements and monitor the sound in real-time to evaluate and make adjustments (Brown et al., 2015). Previous empirical studies suggest that expert musicians have a better capacity to control their motion and minimize muscle effort relative to less-skilled musicians (Furuya & Kinoshita, 2007, 2008), and experts can perform accurately and expressively without auditory or other types of sensory feedback (Finney & Palmer, 2003; Gabrielsson & Juslin, 1996). The present study compared two datasets from a world-renowned string quartet and a student string quartet to explore whether the expertise would influence musicians' group-level cardiac dynamics. We expect that the Danish String Quartet (expert group) will have a higher level of synchrony and more resistance to adverse experimental conditions compared with the Borealis String Quartet.

1.3 Contribution

The present study aims to investigate the cardiac dynamics and synchrony in string quartet performances. As far as we know, this is the first study to examine musicians' cardiac activity in string quartet performances, as well as the first study to utilize both linear and nonlinear techniques to capture cardiac synchrony in instrumental musical ensembles. Our findings provide the first evidence that playing in the string quartet promotes the predictability of cardiac dynamics and cardiac activity synchronization. The synchrony rate may be influenced by adverse performance conditions depending on the level of expertise. Besides, the author of this thesis contributed to the MusicLab Copenhagen project as a research assistant by participating in the project preparation, conducting EKG data collection, EKG dataset pre-processing, and writing the corresponding technical documentation for the MusicLab Copenhagen Dataset[4] (Høffding et al., 2021) published on Open Science Framework, which is an open-access dataset that includes all the audio, video, physical, and physiological data we collected during the project. These data can be further shared and processed for future open science research. Lastly, this thesis will be partially re-write and published as a separate article collaborating with Dr. Simon Høffding, Dr. Victor Gonzalez Sanchez, Eigil Yuichi Hyldgaard Lippert, and Dr. Sebastian Wallot.

1.4 Key Concepts

In an effort to address the interdisciplinary scope of the present study, a set of terms and analytical units are explained preemptively. Specifically, these definitions aims to clarify the basic terms regarding cardiac activity and nonlinear dynamics.

- **Cardiac Dynamics** - Cardiac Dynamics describe and focus on the dynamic phenomena occurring in and around the heart. Born from the interaction of two different disciplines: medicine and physics (Baan et al., 1980).

- **Electrocardiogram (EKG)** - EKG is an electrogram of the heart which is a diagram of voltage versus time of the bioelectrical activity using electrodes attached to the skin (Lilly, 2016).

- **R-R interval** - R-R interval refers to the interval between two successive R-waves of the QRS signal (Figure 1) on the electrocardiogram. Larger R-R intervals indicate a slower heartbeat, while smaller R-R intervals indicate a faster heartbeat.

- **Heart Rate (HR)** - HR refers to the heart contraction speed measured by the beats per minute (BPM) or the average R-R interval. An increase in BPM or a decrease in average R-R interval usually suggests higher emotional arousal or cognitive effort (Wright et al., 2022).

- **Heart Rate Variability (HRV)** - HRV describes the variation for time elapse between successive heartbeats. A decrease in HRV usually

[4] See https://osf.io/v9wa4/

indicates increased physiological arousal or alertness (Wright et al., 2022).

- **SDNN** - SDNN is one of the time-domain metrics of HRV, measured by the standard deviation of the interbeat interval of normal sinus heartbeats (Shaffer & Ginsberg, 2017).

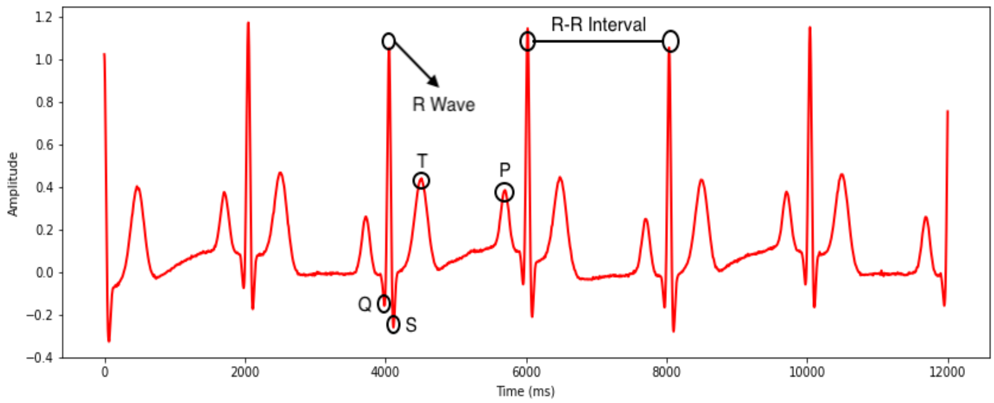
- **Nonlinear Dynamics** - Nonlinear dynamics is the phenomenon that occurs in nonlinear systems, commonly found in biological and mechanical systems. It describes changes in variables over time, which may appear chaotic, unpredictable, or counterintuitive, contrasting with much simpler linear systems (Kia et al., 2017; 'Nonlinear System', 2022; Scott, 2007).

- **Entrainment** - Entrainment originally refers to the temporal locking process of two oscillation systems, which can be traced back to when Physicist Christiaan Huygens observed two pendulum clocks become synchronized on the same surface in 1666. This phenomenon has been found in many mechanical and biological systems; typical physiological activities such as cardiac response, breathing, neuron firing, or body motion can be conceptualized as oscillators. Entrainment not only represents the period or phase coordination between two oscillators but also describes the tendency toward a synchronized state. In this thesis, entrainment refers to the coupling process of the human body motion or physiological frequency to an external rhythm (J. Trost et al., 2017).

- **Synchronization** - The definition of synchronization is similar to entrainment, yet the distinction between the two is still debatable, depending on the specific field and context. Compared with entrainment, synchronization does not require an oscillator (Bittman, 2021) and can be used to describe the coordination between two regular events. We believe that synchronization emphasizes the coordinated phenomenon rather than the process or tendency. In this thesis, these two terms are used synonymously since both concepts are often conflated in previous studies, and the distinction is not radical in our context.

- **Interpersonal Synchrony** - Interpersonal synchrony is the phenomenon in which the movements or sensations of two or more people coincide, which is commonly observed in the group activity.

Figure 1.
The illustration of R-R Interval



1.5 Thesis Outline

This thesis consists of five chapters. The first chapter introduces the motivation, research questions, contribution, and clarification of the key concepts. Chapter 2 provides an overview of the theoretical background and summarizes the empirical studies related to the topics and methodologies investigated in this thesis: sensorimotor synchronization, music and cardiac activity, and physiological synchronization in music activity. Chapter 3 describes the experiments as well as the analytical and data validation methods we applied for the present study. Chapter 4 demonstrates the results corresponding to the research questions raised in the introduction section. Chapter 5 offers an in-depth discussion of the thesis' results in relation to cardiac dynamics and synchrony and highlights our contributions to the fields of music cognition, concluding with a general reflection and suggestions for future research.

Chapter 2

Background

In this chapter, we provide an overview of the most important concepts and previous empirical studies related to the topics of the thesis. In the first section, we start with the introduction of embodied music cognition, to further explain the motivation and theoretical background of the present study by illustrating the phenomena and mechanisms regarding sensorimotor synchronization in the musical ensemble. In the second section, studies related to cardiac activity during music listening and performance are addressed for reference. Finally, we end with reviewing the evidence regarding the physiological synchronization in joint music activity.

2.1 Sensorimotor Synchronization and Musical Ensemble

With the prosperous development of embodiment theory, embodied music cognition has become increasingly influential in music research. Embodied music cognition considers the human body as the natural mediator to link the mind and environment, processing music intentions and meanings (Godøy & Leman, 2010; Jensenius, 2007; Leman, 2008). In contrast to the classical music cognition paradigm, which upholds the dissociation of body and mind, embodied music cognition considers the body inseparable from the cognitive process and is being applied and supported by substantial empirical works. Sensorimotor synchronization is an extensively studied topic and is deemed closely related to embodied theory. It refers to the temporal coordination between rhythmic movement and external beat, ranging from finger tapping along with the metronome to physical coordination in musical ensemble performance (Leman & Maes, 2014; Repp, 2005; Repp & Su, 2013).

Musical rhythm tends to induce body motion (Wright et al., 2022; Żelechowska, 2020), and even those not trained in music can generally move along with the beat (Repp, 2010). The ability to move in synchrony with external rhythm is inherent in humans and is fundamental to dance and various music activities. Previous studies suggest that infants already tend to move rhythmically with music (Provasi & Bobin-Bègue, 2003) and exhibit more spontaneous movement when listening to music (Zentner & Eerola, 2010). And people can coordinate their actions with collaborators both intentionally and unintentionally to the rhythm. For instance, Néda et al. (2000) described the thunder of applause after a good performance always unintentionally turning into synchronized clapping in a short period at the beginning, which can disappear and reappear several times throughout the applause. Moreover, Clayton (2007) observed and analyzed a video recording of the Indian raga performance, which revealed evidence of unintentional synchronization of their behavior, even though musicians do not seek to coordinate their movement. Similarly, Lucas and her colleagues (2011) examined the synchronization between independent groups of musicians in Afro-Brazilian Congado performances. Although researchers told the different groups to avoid synchronization, they still observed periodic synchrony between separate groups of performers. In addition, researchers recruited one hundred adult participants and let them move freely in groups of five along with the musical sequences at the different sound pressure levels of the bass drum. They demonstrated clear group synchrony in participants' behavior and found an increased degree of entrainment in higher sound pressure levels of the bass drum (Van Dyck et al., 2013).

Performing music together requires precision temporal coordination to enable synchrony with sound and achieve common music intentions. Previous studies revealed that expert musicians have extraordinary motor control ability. Compared with less skilled pianists, expert pianists have better independence and efficiency in their fingers and upper-limb movements by minimizing and optimizing their muscles' coordination processes as a result of extensive practice (Aoki et al., 2005; Furuya et al., 2011; Furuya & Kinoshita, 2007, 2008). Besides, skilled pianists can play and synchronize with millisecond-level precision and maintain a less than 3% error accuracy (Palmer, 1997, 2006; Repp, 1992, 2005, 2010). Except for the precise execution of their performance, skilled musicians also need to monitor the sound and adjust their motions in real-time to ensure the quality and desired music intention (Brown et al., 2015). This process involves a combination of auditory, visual, tactile, and even vestibular feedback (Brown et al., 2015; Finney & Palmer, 2003; Gabrielsson, 2003; Repp, 1999), which allows musicians to better perceive, remember, and reproduce expressive changes in music (Chaffin & Lisboa, 2008; Clarke, 1989, 1993).

As a result of the development of highly accurate motion capture technologies, more attention has been addressed to the mechanisms of temporal coordination in the musical ensemble. For instance, Moore and Chen (2010) analyzed the coordination between two string quartet players in a task that required musicians to play a musical passage with hundreds of uniform notes rapidly at a stable speed in synchrony. They found two musicians could effortlessly maintain a high degree of temporal precision, and there was a similar timing microstructure of their interactive behavior. In addition, researchers found auditory feedback and visual cues affect musical ensembles. Goebl and Palmer (2009) explored the influences of auditory feedback and musical roles of leader and follower on the synchronization in piano duet performances. The sound and motion analysis illustrated that the temporal asynchronies increased when the auditory feedback decreased. Visual information became more important since pianists raised fingers higher and more synchronized in head movements when auditory feedback was absent, regardless of assigned musical roles. Moreover, piano duettists revealed greater asynchronies in the duo piano performance in tone onsets when they lack visual cues compared with the condition they could see each other (Kawase, 2014). Similar results also have been reported in vocal duo performances, where vocalists sang in pairs and performed lower synchrony levels on the first onset in performance without visual cues (D’Amario et al., 2018). Furthermore, Chafe et al. (2010) investigated the influence of time delays on joint music activity by modulating the auditory delays between musicians ranging from 3 to 78 ms and reported that the best coordination happened between 8 to 25 ms, which is similar to the natural delay in the live ensemble.

In addition to exploring the role of sensory information in physical coordination, researchers also examined the influence of individual differences since human performances are not rigorously periodic, and collaborators must adjust to each other in real-time on their tone onsets (Palmer, 2013; Palmer et al., 2019). Loehr and Palmer (2011) demonstrated that duet piano players with similar preferred performance rates were better coordinated and adapted to each other’s timing. Likewise, a series of studies reported the influence of endogenous rhythm, which refers to the spontaneous performance rate of solo performance. They found differences in partners’ spontaneous rates influence temporal coordination in joint musical performances (Zamm et al., 2015), and partners who have more corresponded spontaneous rates showed a lower level of asynchronies in the joint performance than mismatched partners (Zamm et al., 2016).

In conclusion, these studies explored how music induces and synchronizes behaviors. As an extensively explored topic, it revealed that temporal coordination between collaborators in the musical ensemble is affected by the degree of expertise, visual and auditory feedback, and individual differences. Consequently, these studies lead to a series of questions in the context of the present study regarding how music and coordinated behavior influence physiological activity, which will be described in the following section.

2.2 Cardiac Response in Music Activity

Over the past two decades, an increasing number of studies addressed the physiological effects of music activity from the basic physiological response to related higher-level emotion and arousal, with a focus on the autonomic nervous system (ANS), since it plays an important role in this regulated process and its involuntary responses serve as indicators of emotional experience and social engagement (Scherer, 2005; Shaffer et al., 2014). As one of the major and most sensitive physiological markers within the ANS to reflect emotional reactions and both sympathetic and parasympathetic activity (Chuen et al., 2016), cardiac response, is commonly evaluated by heart rate (HR) and heart rate variability (HRV) through electrocardiogram (EKG), which can be measured by specialized sensors or chest bands with built-in electrodes in a reliable, convenient, and noninvasive way. Hence, cardiac activity has become one of the most frequently measured psychophysiological indices for empirical studies related to music.

In this section, we start with reviewing the cardiac responses when people passively listen to music and then present the current evidence regarding the influence of musical performance on cardiac dynamics.

2.2.1 Listening to Music

Most physiological-related studies are grounded in the entrainment theory in which one system's motion or signal frequency tends to synchronize with another system (Thaut et al., 2015; Wright et al., 2022). Therefore, it is intuitive to expect and hypothesize that a higher musical tempo correlates with a higher heart rate and increased arousal, and vice versa. The majority of related experiments focused on the effect of music rhythm on heart rate. For example, in a preliminary study, Bernadi et al. (2006) investigated the effects of music on the cardiovascular and respiratory systems. After a five-minute stationary baseline, they presented six different music styles as stimuli in random order. Results showed an increase in heart rate, blood pressure, and ventilation during faster tempos and a decrease during the pause compared with baseline. Moreover, researchers developed a music-heartbeat feedback system and experimented by modulating the music tempo 10% faster or slower than the participants' heart rates. They reported that participants' mean heart rates were faster during the faster condition and lowered during the lower condition (Nomura et al., 2013). In a more systematically designed study, Chuen et al. (2016) measured cardiac activity, respiration rate, skin conductance, and facial motor activity when subjects listened to rhythmical sequences with changes in tempo, pitch, duration, and intensity. They found that faster musical tempo correlates with higher skin conductance level and heart rate, and changes in acoustic features also lead to an increase in heart rate in the context of the experiment. A further study suggests the entrainment may correlate with participants' resting heart rates. Watanabe et al. (2017) manipulated subjects' basal heart rates by controlling their breath. They discovered that subjects with slow basal heart rates (less than 80 BPM) had an increase while listening to a stimulus at 80 BPM, but subjects with higher basal heart rates (more than 80 BPM) had no acceleration in heart rates.

Nevertheless, few studies did not find any evidence regarding the acceleration effect of heart rate entrainment. For example, in a study that applied Chopin piano pieces in different tempi (56 BPM and 233 BPM) as stimuli, researchers didn't find any influence of fast-tempo music on listeners' heart rates but observed decreased heart rates in the slow-tempo conditions (Ooishi et al., 2017). Similar results were reported in a study conducted by Van Dyck and her colleagues (2017), in which they used non-vocal, ambient music as stimuli, played at a tempo equal, faster, or slower at ±15%, ±30%, and ±45% than participants' resting heart rates - they also demonstrated no effect of fast-tempo music but slower heart rates of slower-tempo music.

In addition, contradictory conclusions were reported regarding rhythmic entrainment with heart rate. For instance, Mütze and her colleagues (2018) conducted an experiment using a simple Djembé-beat as a stimulus. They adapted the sequence to the participants' real-time moving average heart rates by increasing 25%, 40%, or 55% of the stimulus tempo on participants' heart rates. They pointed out no group-level evidence of cardiac entrainment or phase alignment to the rhythm due to the significant individual differences. Also, in a critical literature review, Koelsch and Jäncke (2015) explicitly argued against the simple linear coupling effect between music rhythm and heart rate since there is inconsistent evidence of the effect of music and the heart.

Previous studies have examined the possible synchronization between cardiac activity and rhythm in music or tone sequence, using a variety of different methods. A remaining critical question is whether these results are simply affected by the change of rhythm or if other sound features and experimental variables more profoundly influence the heart rate and thus lead to different conclusions. Additional evidence suggests that the loudness of the music may provoke an increase in cardiac activity. For example, Coutinho and Cangelosi (2013) investigated the relationship between low-level psychoacoustic features (loudness, pitch contour, texture, tempo, and sharpness) and physiological responses (cardiac activity, skin conductance rate) by using nine pieces of

Western music excerpts. The analysis of audio features and subjective rating of arousal illustrated that the heart rate was correlated with subjective arousal rating and loudness index of the music pieces. Similarly, Mikutta et al. (2013) demonstrated that heart rate and self-rating arousal correlated with sound intensity when participants listened to two different rhythmically shaped Chopin "Tristesse". Furthermore, researchers examined subjects' heart rate variability in response to classical baroque music and heavy metal music in different loudness ranges from 60dB to 90dB. They observed a significantly decreased heart rate variability in the loudest range (80 to 90 dB) of a heavy metal music piece compared with the quiet baseline (do Amaral et al., 2015). Moreover, Cheng and Tsai (2016) examined female listeners' autonomic responses to soft (sea sounds) and loud music (heavy metal songs) passages. Results showed a higher heart and respiration rate when listening to loud music and a lower heart rate during soft passages.

Besides, in two consecutive studies, researchers compared participants' heart responses when listening to classical baroque music (slow condition) and heavy metal music (fast condition) with a quiet baseline. The major difference between these two studies is that the first study (da Silva et al., 2014a) applied a twenty-minute version of musical pieces. In contrast, the second study (da Silva et al., 2014b) used five-minute stimuli instead. It contributed to different results as the first study found no differences between conditions in heart rate variability while the second study observed decreased overall heart rate variability compared with baseline when participants listened to fast tempo excerpts. Therefore, the distinctions may indicate that the cardiac activity was affected by the perceived musical duration.

Several studies explored other possible factors that influence heart activity. Sills and Todd (2015) compared the heart rates when participants listened to different genres of music. They found the average heart rates were significantly increased after they were exposed to rock music and decreased to classical music as well as their favorite selections, even though the rock music has the slowest tempo among the stimuli, which suggests listening to different music genres may influence the heart activity. In addition, Egermann et al. (2015) conducted a cross-culture study to investigate participants' subjective and psychophysiological responses to music from two different cultural backgrounds. They recruited forty Canadians without any experience with Congolese music and forty Congolese Pygmies who were never exposed to Western music before to listen to Western classical music and Pygmy vocal music. In general, participants' heart rates were correlated with faster-tempo music. However, decreased heart rates were reported in Pygmies when they listened to Pygmy music, while Canadians only responded with increased breathing rates and had no effects on heart rates. Hence, their findings partially indicate that participants' cardiac activity may be associated with cultural familiarity with the music. Furthermore, Lynar et al. (2017) conducted a physiological comparison between two assigned musical pieces (Jazz and Classical), an “uplifting” self-selection, white noise, and a quiet baseline. They demonstrated heart rate was the highest and heart rate variability was the lowest during self selections compared with all other excerpts, which suggest the greatest physiological arousal in all conditions. Thus, this study further establishes that familiarity with the music or music genres can impact cardiac responses to the music.

Listening to music can evoke emotions and regulate moods (Eerola et al., 2018; Eerola & Vuoskoski, 2013). Studies have explored the relationship between music emotions and physiological responses. Sammler and her colleagues (2007) found that dissonant music (unpleasant) evoked a substantially lower heart rate than pleasant music. This finding also coincided with the earlier conclusion that sad music induces a decrease in heart rate (Krumhansl, 1997). However, Krabs et al. (2015) presented opposite evidence as they observed an increase in heart rate and a decrease in heart rate variability during both pleasant and unpleasant music, and there was no difference in autonomic nervous system effects when people perceive two kinds of stimuli.

While a large number of publications have examined the relationship between various musical elements and physiological responses, limited studies have focused on the influence of musical experience and expertise on cardiac activity when people passively listen to music. Dellacherie et al. (2011) investigated the influence of music experience on the emotional response to music dissonance by measuring physiological responses. Results showed that participants with high musical experience had a strengthened aversion to dissonance, but researchers did not observe a significant change in heart rate and skin conductance rate. Besides, Vieillard et al. (2012) explored the effects of music expressiveness on musically trained and untrained participants’ physiological responses and subjectively perceived emotions. Both trained and untrained listeners were exposed to three kinds of music excerpts with different emotions (happiness, sadness, scare) and two levels of expressiveness (expressive, mechanical). Although subjective ratings indicated that the expressive condition resulted in more intense emotional responses in music experts, the researchers did not observe substantial variation in cardiac activity or any other physiological measures. These findings indicate that while music experts may be more sensitive and emotionally active with the music features, such differences were not distinguished at the physiological level.

In summary, these studies suggest that cardiac response may be associated with rhythm, loudness, duration, genres, music emotion, and familiarity when passive listening to music. It is also apparent that previous studies did not provide aligned and sufficient evidence to reveal the mechanisms of cardiac activity in response to music listening, especially the relationship between musical tempo and heart rate is still debatable. The controversies may be due to the sample size in previous studies not being large enough (the quantity of participants is around 20), the heterogeneous methods applied in experiments (Kölsch & Jäncke, 2015), or the interference of different variables in the perception of stimuli. Therefore, future research is needed to delve into the contribution of different elements of music to cardiac activity on a more consistent scale of variables in experiments (e.g., fixed music tempo range for different conditions, fixed modulation rate of the tempo, loudness, etc.).

2.2.2 Musical Performance

Compared with listening to music, performing music is a more involved and engaging activity, demanding higher mental effort (Endestad et al., 2020) and extremely precise control of their motion (Furuya & Kinoshita, 2007, 2008; Gonzalez-Sanchez et al., 2019). Therefore, performing music may elicit higher emotional arousal and different physiological responses.

Fewer studies have investigated musicians' cardiac activity while they perform music. De Manzano et al. (2010) collected twenty-one pianists' physiological responses (cardiac activity and respiration) during the piano solo performances. Each pianist selected a music piece, repeated it five times during the experiment, and provided a subjective report regarding the experienced "flow" after each repetition, indicating the level of positive emotional engagement during the performance. Researchers found an increased heart rate and decreased heart rate variability during the piano performance, and cardiac activity positively correlated with increased self-ratings of flow.

Nakahara et al. (2011) explored the differential effects of heart rate and heart rate variability while playing and listening to the piano. They selected a well-tempered Bach *Clavier, Vol. I, Prelude No.1,* and instructed 16 pianists to perform in three conditions: normal performance with expressive emotions and motions, performing without emotions and ancillary motions, performing without emotion and using a forte-touch throughout the performance. In addition, all the participants heard their own performances. Unsurprisingly, lower heart rate and higher heart rate variability were in the listening conditions compared with performing, and higher heart rate and lower heart rate variability in the normal expression conditions than in the performance conditions without emotions. Moreover, the self-reported arousal and pleasant level were positively correlated with increased heart rate. Thus, these findings confirmed that musical performance was more effective in evoking emotional arousal and modulating cardiac activity than passive listening to music.

Moreover, Harmat et al. (2011) recruited three internationally well-known solo pianists and compared cardiac and respiratory responses when they performed a self-selected music piece (familiar and easy for them) and an unfamiliar difficult prima vista piece. They observed a higher heart rate and a lower respiration rate during the familiar music piece than during the difficult unfamiliar piece. On the other hand, Blasco-Lafarga et al. (2020) investigated the heart rate and heart rate variability when musicians played different difficulty levels of wind music pieces. Although there was an increase in heart rate variability indices during the difficult condition, the heart rate didn’t change at all. Different results between these two studies may be because the performances on wind instruments demand musicians deliberately change their breath with music, which is reflected in their cardiovascular system.

Besides, researchers investigated the effects of anxiety on cardiac activity during musical performances. Brotons (1994) examined the differences in musicians’ physiological and psychological responses between non-jury and jury conditions. Results demonstrated that heart rate and self-reported anxiety index increased during jury conditions. Similarly, LeBlanc et al. (1997) conducted a study to test twenty-seven high school band members performing in three different conditions: performing alone, performing with one researcher, and performing with all researchers. They found heart rate was stable during the first two conditions but significantly increased when performing in front of all researchers. Moreover, a significantly increased heart rate has been found during public performances compared with rehearsal, when researchers monitored the cardiac activity of twenty-seven professional musicians' performances (Vellers et al., 2015). These studies indicate that musicians performing in front of audiences may increase their anxiety level, reflecting their cardiac activity.

Last but not least, in a recent study, Wright and Palmer (2020) pioneering applied both linear and nonlinear methods to study the pianists’ cardiac activity during music solo performances. They examined the cardiac dynamics of familiar and unfamiliar music excerpts at different times of the day using Recurrence Quantification Analysis (RQA). Results demonstrated participants’ cardiac activity patterns were more predictable and stable for unfamiliar excerpts as well as the performance in early times (9 am and 1 pm), and heart rate was higher during the musical performance than during the quiet baseline. Compared with linear analysis, the nonlinear method captures a different perspective of cardiac activity not demonstrated by the linear method.

Overall, fewer studies have explored the cardiac dynamics of musical performances as opposed to listening to music. Most studies suggest that the musical performance facilitates emotional arousal, resulting in an accelerated heart rate. However, as Wright et al. (2022) pointed out, studies related to the music and heart have only applied linear methods to examine its activity, despite the fact that the nature of cardiac dynamics is nonlinear and nonstationary, and linear measures are unable to examine the nonlinear perspective of cardiac patterns (e.g., Krogh-Madsen & Christini, 2012; Qu et al., 2014; Webber & Jr, 2012). Therefore, this thesis aims to bridge this gap and utilize both linear and nonlinear techniques to investigate the cardiac dynamics in string quartet performance.

2.3 Physiological Synchronization in Music Activity

There is still a lot of discussion regarding the role of music in the human evolution process. One of the prevailing arguments is that music may be developed as a tool to create and strengthen social connections among interacting groups of people (Dunbar, 2012; Kogan, 1997). In this sense, the different levels of synchronization in joint music activity may play a critical role in this process since synchronized behaviors have been demonstrated to promote group cohesion and rapport among group members (Cohen et al., 2010; Hove & Risen, 2009; van Baaren et al., 2004; Wiltermuth & Heath, 2009). In addition to motor and neural synchrony, cardiorespiratory synchrony has received substantial attention in topics related to interpersonal synchrony in social activities. For example, researchers have reported cardiac synchrony in individuals in a traditional Spanish fire-walking ritual (Konvalinka et al., 2011), co-sleeping (Yoon et al., 2019), watching movies together (Golland et al., 2015), and mother-child interactions (Busuito et al., 2019). These studies demonstrate that synchronized behaviors, shared experiences, and similar emotions may promote synchronization at the physiological level when engaging in group activities.

However, as we mentioned in the last two sections, while many studies thoroughly investigated motor synchronization in musical ensembles and cardiac responses influenced by music, limited studies have explored the phenomena of physiological synchronization. Recent studies have shown that common behaviors and coordinated movements in joint music activity may contribute to a similar entraining process on physiological responses. Müller and Lindenberger (2011) provided the first evidence regarding the physiological synchronization in joint music activity. They measured eleven singers and one conductor’s cardiac activity and respiration when they sang in a choir. The phase synchronization increased significantly in heart rate variability and respiration during the musical performance compared with a resting baseline. Besides, the cardiorespiratory patterns suggest that when musicians sing in unison, the phase synchrony level is higher than when they sing in parts. Similarly, Vickhoff and his colleagues (2013) investigated how singing in a choir influences heart rate variability and respiratory sinus arrhythmia (the coordination of respiration to heart rate variability). They reported that the song's structure influences respiration, and singing together makes singers' heart rates increase and decrease simultaneously. Moreover, Ruiz-Blais et al. (2020) explored the heart rate variability synchronization when non-experts sing in dyads. Similar to the previous studies, they demonstrated that heart rate variability remained synchronized even in non-professional duets, and the coupling rates were not related to the subjective rating of unity.

In addition to singing together, Bernardi and his colleagues (2017) explored the musical physiological bonding hypothesis by examining the physiological rhythms between individuals when listening to music together. This hypothesis suggests that music can affect the individuals’ physiological activities in a similar way and synchronizes the physiological rhythms in a group. Consistent with the theory, they found a subtle but reliable increase in synchronization of cardiorespiratory rhythms when two groups of people listen to live Christian religious music in a church for two days. Besides, different stimuli caused a varied level of synchrony, which may be related to the complexity of the loudness profile of the music.

In sum, the mechanisms of physiological synchrony during the musical ensemble still remain unclear since previous studies have only examined evidence of cardiac synchrony during choral singing. Singing together demands musicians’ to deliberately control their breath according to music phrase and structure, which is highly correlated with cardiac activity and may modulate autonomic nervous system responses. Hence, the conclusion that singing together can promote the coupling of heart activity cannot simply be equated to the instrumental ensemble. To our knowledge, there are no empirical studies that have observed the phenomenon of physiological synchrony among musicians in instrumental musical ensembles. Besides, its mechanisms have not received sufficient attention either. As reviewed in the previous sections, motor coordination and physiological responses to music are influenced by various factors. Whether these factors similarly affect physiological synchrony in the musical ensemble has not been established. In the following sections, we present two case studies to investigate cardiac synchrony in string quartet performances in multiple experimental conditions that differ in communication constraints and the level of familiarity with music, intended to contribute to the current knowledge of physiological synchrony in the musical ensemble.

Chapter 3

Methods

3.1 Experimental Design

The experiments are part of the MusicTestLab and MusicLab Copenhagen projects conducted by the RITMO center of excellence, University of Oslo, Norway. Specifically, the present study includes the analysis of the cardiac data in the Musiclab Copenhagen Dataset (Høffding et al., 2021) from two string quartets: the Borealis String Quartet (BSQ) and the Danish String Quartet (DSQ).

The experiment of BSQ was conducted in the Motion Capture Lab of RITMO at the University of Oslo in Oct 2020. The BSQ performed the same music excerpt six times under five different experimental conditions in order (Table 1). The first five performances were held in conditions similar to rehearsals; four musicians were performed alone, without examiners present. The sixth condition (Concert) was conducted under a simulated concert environment with researchers in attendance (Bishop et al., 2021).

The DSQ's experiment was carried out in the Musikhuset København (Copenhagen Concert Hall), Denmark, in Oct 2021 as part of the "science concert" event within the MusicLab Copenhagen project. The DSQ played the same repertoire and kept most experimental settings as BSQ in the previous Music Testlab project. In addition to the six original conditions, we have added two conditions: Moving Baseline and Sight-reading conditions (Table 2), as references to better investigate the mechanisms in cardiac dynamics during quartet performances. All experiments received approval from the University of Oslo and the Norwegian Center for Research Data (NSD).

Table 1
Experimental conditions of the Borealis String Quartet

Condition	Description
Quiet Baseline	Quartet members have seated together in preparation for the experiment and have no body motion for 40 seconds.
Blind	Quartet members played the Haydn excerpt while facing away from each other so they couldn't see each other at all (Figure 2).
Score-directed	Quartet members played the Haydn excerpt while facing each other normally but were only allowed to look at the score.
Normal	Quartet members played the Haydn excerpt while facing each other normally & looking wherever they wanted.
Violin-isolated	Quartet members played the Haydn excerpt while the 1st violinist was hidden behind a curtain; the others were allowed to look at each other normally.
Normal-repeated	The replicate condition of Normal, the quartet played the Haydn excerpt while facing each other normally & looking wherever they wanted.
Concert	Quartet members played the full first movement of the Haydn for an audience of about 30 researchers; they were configured normally and allowed to look wherever they wanted (Figure 3).

Table 2.
Experimental conditions of the Danish String Quartet

Condition	Description
Quiet Baseline	Quartet members have no body motion. Eyes fixed on the center of the music score for three minutes.
Moving Baseline	Quartet members played a slow scale together in synchrony while their eyes were fixed on the music score.
Blind	Quartet members played the Haydn excerpt while facing away from each other so they couldn't see each other at all (Figure 4).
Score-directed	Quartet members played the Haydn excerpt while facing each other normally, but were only allowed to look at the score.
Normal	Quartet members played the Haydn excerpt while facing each other normally & looking wherever they wanted.
Violin-isolated	Quartet members played the Haydn excerpt while the 1st violinist was hidden behind a curtain; the others were allowed to look at each other normally (Figure 5).
Normal-repeated	The replicate condition of Normal, quartet members played the Haydn excerpt while facing each other normally & looking wherever they wanted.
Sight-reading	Quartet members played Langgaard's String Quartet No. 5, 2nd movement, which they had never played or heard before.
Concert	Quartet members played the full first movement of the Haydn for an audience of about 30 researchers; they were configured normally and allowed to look wherever they wanted.

Figure 2.
BSQ in Blind condition

Figure 3.
BSQ in Concert condition (with audiences)

Figure 4.
DSQ in Blind condition

Figure 5.
DSQ in Violin-isolated condition

3.2 Participants

The Borealis String Quartet is a student quartet from the Norwegian Academy of Music (NMH). The musicians were 20-21 years old (one female, three male) and had been playing together for about half a year. The Danish String Quartet is one of the most well-known string quartets in the world and was established over twenty years. The musicians were 39-40 years old (four male). As *ECM Recording Artists* and *GRAMMY-nominated* musicians, they have released eleven albums, conducted several world tours, and won numerous international chamber music awards. All participants consented to collect physiological data and provided the written consent form.

3.3 Materials and Equipment

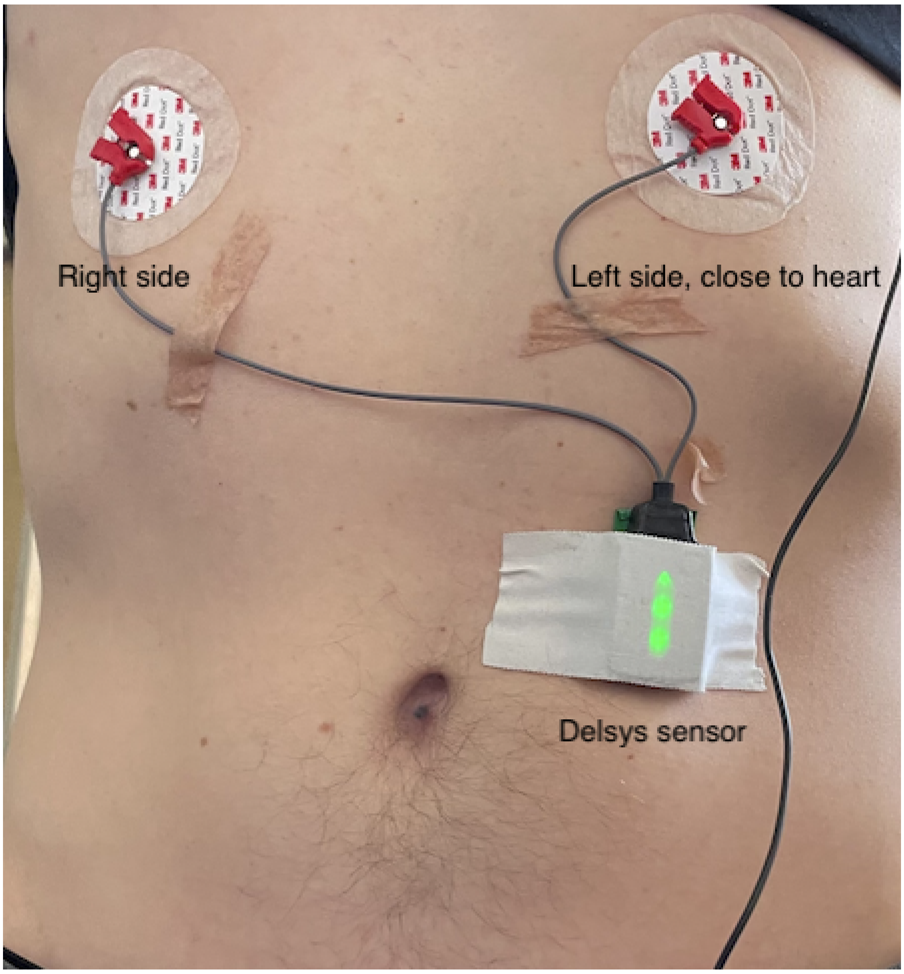
Two quartets played the first 68 bars of the *String Quartet in B-flat major, Op. 76, No. 4, Allegro con spirito*, by Joseph Haydn in performance conditions include Blind, Score-directed, Normal, Violin-isolated, Normal-repeated, and the complete first movement in Concert condition. In the Sight-reading condition performed by DSQ, the quartet played Rued Langgaard's *String Quartet No. 5, 2nd movement*, which they had never played or heard before.

The electrocardiogram (EKG) was obtained for four musicians (Violin I, Violin II, Viola, Cello) in the string quartet by applying four Delsys Trigno EKG sensors on their chests. The EKG sensor consists of one main sensor body with two cabled detection leads clipped to snap electrodes. The two cabled electrodes were placed parallel to each other under the pectoral muscles, with the shorter cable side positioned close to the participants' hearts (Figure 6). All EKG sensors were cleaned with alcohol wipes before the experiment, and the wires and sensor's main body were secured with medical tape to avoid increased noise from possible sensor shifting. All the data was transmitted through Bluetooth to a Lab HP laptop computer in real-time via Delsys host base, with a sampling rate of 1926 Sa/s.

3.4 Procedure

Similar procedures were taken for both experiments. After the equipment setup and a short warm-up period, the recording session began. In the DSQ's experiment, we first recorded a three minutes Quiet Baseline and a Moving Baseline. In the BSQ experiment, we did not specifically record the performers' resting heart rates. Instead, we selected forty seconds of resting before the first Blind condition as a substitute baseline. Musicians have a short break between each performance condition, and researchers reposition musicians according to the experimental design. During these pauses, musicians could chat and discuss previous performances, and each break's duration was approximately the same. On the day of the experiment, all participants kept their habitual sleep and coffee intake and did not report any hearing loss, mental illness, and physical discomfort.

Figure 6.
Placement of the EKG sensor



3.5 Data Analysis

The present study utilizes both linear and nonlinear analyses of cardiac activity data from two string quartets. The linear analysis mainly focuses on variations in Heart Rate (HR) and Heart Rate Variability (HRV) in different performance conditions. For nonlinear analysis, we apply the novel recurrence-based methods to examine the individuals' cardiac dynamics and interpersonal synchrony levels between the musicians at different levels. All these data are compared between different experimental conditions, and between two string quartets.

3.5.1 Pre-processing

The EKG data was preprocessed, and R-R intervals were calculated using the Python package Neurokit 2 (Makowski et al., 2021). To address potential inaccuracies related to incorrect heartbeats and signal artifacts (Peltola, 2012), we performed the Python package Systole (Legrand & Allen, 2022) and visual inspection to ensure the artifacts were properly removed from the data. For nonlinear analysis, since the R-R intervals typically have inconsistent data lengths across participants due to individual differences in heartbeat frequencies, we transformed the R-R intervals to the BPM data by oversampling the time series to 500 ms intervals in advance, to obtain time series of the same rate for each participant within the quartet, also to enhance the sensitivity of recurrence analysis (Wallot et al., 2013). Besides, we intercepted the BPM data for the first 68 bars of the two quartets playing in the Concert condition to facilitate a time-consistent comparison with other conditions.

3.5.2 Calculation of Heart Rate and Heart Rate Variability

Based on the R-R interval we extracted from the EKG data, we used the built-in functions of the Python package Neurokit 2 (Makowski et al., 2021) to calculate the HR (in average R-R interval) and HRV (in SDNN) for four musicians and averaged the data in group level for comparison of different performance conditions.

3.5.3 Calculation of Cardiac Dynamics and Synchrony level

We applied Recurrence Quantification Analysis (RQA) and Multidimensional Recurrence Quantification Analysis (MdRQA) (Wallot, Roepstorff, et al., 2016) to measure the nonlinear dynamics and synchrony level between the cardiac data of different musicians.

RQA is a nonlinear technique to examine dynamical systems such as behavioral and physiological activities (Dimitriev et al., 2020; Javorka et al., 2009; Marwan et al., 2007) by applying a higher-dimensional reconstruction method (Takens, 1981) to analyze recurrent states in one dimension signal. Additionally, MdRQA is a multivariate recurrence-based method developed on RQA to capture the repetition of the same or similar values between multi-dimensions time series. Compared with RQA, the MdRQA can be implemented to examine the group dynamics and synchrony levels for multiple participants at different levels (Wallot & Leonardi, 2018). The recurrence-based analysis features robust procedures to address outliers and heterogeneous variance over time (Marwan et al., 2007). Therefore, RQA and MdRQA were particularly suited to investigate the cardiac dynamics and synchrony measures in the present study.

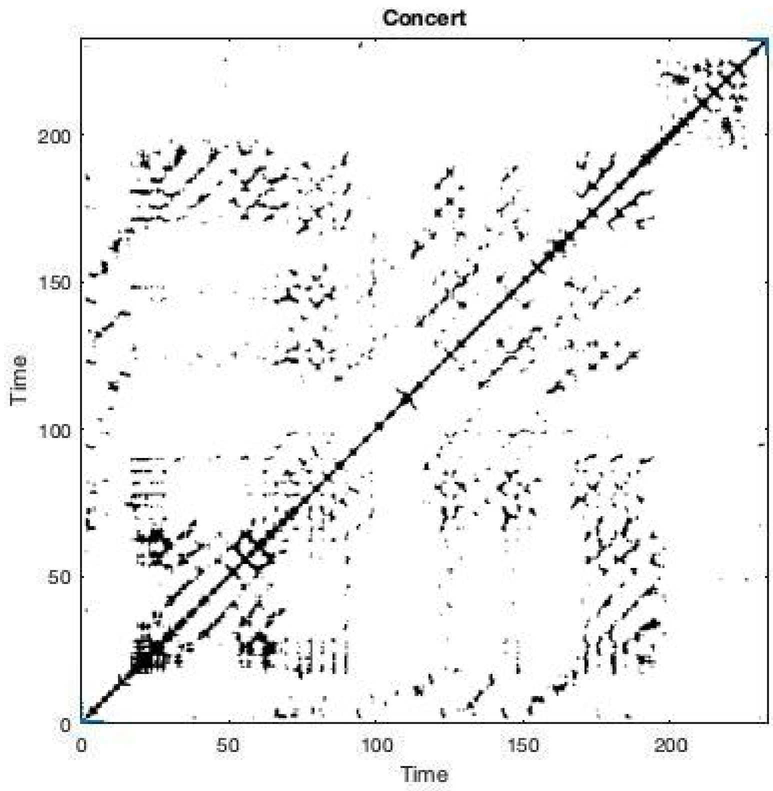
To be more specific, both RQA and MdRQA were derived from the recurrence plot (RP), a two-dimensional visualization of the recurrent behavior in dynamic systems (J.-P Eckmann et al., 1987). The RP is a symmetric matrix with identical time series along the x and y axes (e.g., Figure 7). That is, projecting time-delayed copies of the time series into a multidimensional phase space, when the trajectory visits the same coordination, or within a certain range in the phase space again, through the calculation of the euclidean distances between coordinate pairs of data points in time series, the distances below the threshold are determined as recurrent, dots are marked on the plot, identify as recurrent points (Gordon et al., 2021; Wallot, Roepstorff, et al., 2016; Wallot & Leonardi, 2018). This can be formally expressed as

$$R_{ij} = \Theta\left(r - \|X_i - X_j\|\right), i, j = 1, \ldots, N, \tag{1}$$

where R is the thresholded distance matrix; $\Theta(x)$ is the Heaviside step function ($x < 0$, $\Theta(x) = 0$;$x \geqq 1$, $\Theta(x) = 1$); X represents the time series, and $II...II$ is a distance norm; N is the number of data points; r is the threshold parameter (radius) of the recurrence analysis (Wallot, Roepstorff, et al., 2016).

Figure 7

The RP of DSQ Cello's cardiac activity under Concert condition



Note: *RP is symmetrical along the diagonal. Each black dot (i, j) represents a recurrence point, i on the x-axis denotes the time that the trajectory crossed this area in phase space for the first time, and j on the y-axis denotes the time it revisited the area (Konvalinka et al., 2011).*

Recurrence-based analysis requires reconstructing the phase-space profile to properly capture time-series dynamics (Wallot & Mønster, 2018). Since the recurrence-based analysis used the time-delayed embedding method (Takens, 1981) to reconstruct the higher dimensional phase-space, one needs to calculate two parameters: The delay parameter *tau*, represents the delay plotting the time series against itself. And the embedding parameter D, indicates the number of dimensions that needs to be embedded in the reconstructed phase-space. The estimation methods for these parameters varied based on the dimensionality of the input data. The calculation methods applied in the present study will be elaborated on in the following sections.

Both RQA and MdRQA generate multiple outcomes that provide different strategies to quantify features for recurrence plots regarding the dynamics of time series (Webber & Zbilut, 1994; Zbilut et al., 2002). RQA was developed to analyze and evaluate the system's stability, complexity, etc. (Marwan et al., 2007), and MdRQA aimed to examine the shared dynamics of multiple systems (Wallot, Roepstorff, et al., 2016). Specifically, the most commonly applied variables include: %REC (the percentage of recurrent points in the recurrence plots), %DET (the percentage of recurrent points forming diagonal lines), %LAM (the percentage of recurrent points forming vertical lines), ENT (Shannon information entropy of the line length distribution), AVG (the length of the average diagonal line), etc. (Wallot, Roepstorff, et al., 2016; Zbilut et al., 2002). All these variables represent different aspects of the dynamics analyzed by recurrence-based analysis. Their definitions vary based on the specific method and input data, which will be further explained in the context of the present study.

Cardiac Dynamics Analysis

We applied the RQA to analyze the cardiac dynamics of individuals in the quartets by the Python package PyRQA (Rawald, 2018). To better assess and compare the individual cardiac dynamics, we used false-nearest-neighbor (FNN) and average mutual information (AMI) in the Python package Teaspoon (Myers et al., 2020) to estimate the delay parameter tau and the embedding parameter D for one-dimensional time series; where *tau* was determined as the first local minimum of the AMI of the time series (Fraser & Swinney, 1986), and D was chosen as a point close to zero of the FNN function since it demonstrates the signal is sufficiently projected to higher dimensions (Wallot, Roepstorff, et al., 2016; Wallot & Leonardi, 2018; Webber, 2005; Wright & Palmer, 2020). When these functions did not reveal a clear zero point or local minimum point, a point of no change was selected instead. In our study, the embedding parameters D were determined on an individual basis and ranged from 2 to 4, and the delay parameter *tau* resulted from 3 to 16. In addition, for Recurrence Rate, the percentage of recurrence points (%REC) in RQA, was fixed at 5% for individuals' data in each performance condition to determine the euclidean radius r (Javorka et al., 2009; Wright & Palmer, 2020).

The %DET was applied to quantify the observed recurrence in the BPM data, where the minimum number of points required to be considered a line in the calculation was set to two. In RQA, %DET demonstrates the level of the predictability of a system over time (Webber & Zbilut, 1994), are based on the measures for histogram $P(l)$ of the length of diagonal lines l in the RP (Marwan et al., 2007), which can be expressed as equation 2. We averaged four individuals' %DET in a quartet for each experimental condition for comparison.

$$\%DET = 100 * \frac{\sum_{l=lmin}^{N} lP(l)}{\sum_{l=1}^{N} lP(l)} \quad (2)$$

Cardiac Synchrony Analysis

We implemented the MdRQA script developed on MATLAB to systematically investigate different levels of synchrony, from the individual to the whole group (Wallot, Roepstorff, et al., 2016). We analyzed two kinds of synchrony measures by MdRQA for the BSQ and DSQ: (1) group-level synchrony for four musicians in the quartet, (2) averaged individual dyadic synchrony in the quartet.

Similar to parameters estimation procedures for RQA, we applied the multivariate version of estimation methods (Wallot & Mønster, 2018) to estimate tau and D for MdRQA. The same estimation strategy as RQA was implemented on multi-dimensional false-nearest-neighbor (mdFNN) and AMI through the custom MATLAB scripts published by Wallot & Mønster (2018). Besides, the threshold parameter r was determined by yielding the percentage of recurrence points (%REC) from MdRQA among all the conditions between 5% to 10% (Wallot & Leonardi, 2018). Moreover, since the different time series lead to different estimates of the parameters, and MdRQA requires the same parameters for comparison (Wallot, Roepstorff, et al., 2016; Wallot & Leonardi, 2018). We averaged the estimates across the different conditions and rounded them to a set of constants to fit the full sample for cross-comparison. All the parameters applied for MdRQA in our study are presented in Table 3. Finally, all the time series were performed the *z-transform* normalization procedure before being processed to MdRQA, since we were concentrated on the similarities or differences based on the property of the sequential order in the time series, rather than the differences based on the level or variance (Gordon et al., 2021; Wallot & Leonardi, 2018).

In addition to the group-level synchrony comparison between different experimental conditions, we also compared the group-level synchrony between two string quartets in the same condition to address the variations in cardiac coupling levels between two string quartets. Since applying different parameters leads to deviations in the MdRQA results (Wallot, Roepstorff, et al., 2016; Wallot & Leonardi, 2018), we re-performed the parameter estimation with the same strategy and averaged the parameters between the comparison pairs (e.g., the synchrony level of DSQ in Blind condition versus the level of BSQ in Blind condition).

Table 3.
Parameters applied for the MdRQA

Conditions	tau	D	r
DSQ	8	6	0.61
BSQ	5	2	0.41
D & B, Blind	6	4	0.60
D & B, Score-directed	8	4	0.51
D & B, Normal	9	3	0.53
D & B, Violin -isolated	9	4	0.52
D & B, Normal-repeated	7	3	0.51
D & B, Concert	8	3	0.50

Note: *In this table, the conditions marked as DSQ and BSQ represent the parameters applied for MdRQA of group-level synchrony calculation for comparison between different experimental conditions. The conditions marked with D & B represent the parameters used to compare two quartets under the same conditions, respectively.*

Besides, to address the individual contribution to the synchronous activity within the group, we calculated the pairwise synchrony rate for all possible dyads in the group (e.g., violin I and violin II, violin I and cello, violin I and viola, etc.), and averaged the synchrony indices at the individual level. For four musicians in the string quartet, the calculation can be expressed as follow:

$$I(\alpha) = \frac{1}{3}\sum_{\beta} S(\alpha,\beta), \alpha \in \mathcal{S}, \beta \in \mathcal{S}\backslash\{\alpha\}$$

(3)

As shown in the equation above, we denote the set of musicians by $S = \{Violin1, Violin2, Viola, Cello\}$. $S(\alpha, \beta)$ represents the dyadic synchrony level calculated by MdRQA (Wallot, Roepstorff, et al., 2016), $I()$ demonstrates the level of the specific participant's coordination with other members in the quartet (Gordon et al., 2021).

Finally, we choose the %DET as an indicator of synchrony rate based on the following reasons. Firstly, %DET has been proven to reveal synchronous behavior in oscillator systems (Shockley et al., 2002) and has been evaluated in several studies to quantify interpersonal synchrony (Fusaroli et al., 2014; Gordon et al., 2021; Riley et al., 2011; Wallot, Mitkidis, et al., 2016). Secondly, for data with stochastic features, such as BPM or R-R interval, the different measures of MdRQA usually show a similar pattern and are strongly correlated across outcomes (Gordon et al., 2021). Lastly, in the present study, we are interested in shared cardiac patterns over time, which means the time series not only coordinates with each other occasionally but continuously synchronizes in the successive ”trajectories”, which can be properly captured by %DET. Therefore, we select the %DET, with the high absolute values reflecting a high synchrony level while low absolute values indicate low synchrony (Gordon et al., 2021; Wallot, Roepstorff, et al., 2016).

3.6 Data Validation

The data validation consists of two-part. First, for the group-level synchrony measure, since we only have two sets of data and MdRQA only generates one data point for each experimental condition on DET%, we applied a customized bootstrapping MATLAB script developed by Sebastian Wallot (Wallot, Roepstorff, et al., 2016) for data validation. This method calculated the 95% confidence interval based on a bootstrap of the distribution of vertical/diagonal lines of the recurrence plot (Schinkel et al., 2009). In our context, as we have repeated measures data, we modified the method so that the confidence intervals are not based on the bootstrapped data of a single time series but on the differences between the respective pairs of bootstraps. If the confidence interval does not contain 0, this is equivalent to a significance test with $p < .05$. Besides, all statistical analysis was performed with Prism 9 software for the rest of the analysis. The statistical significance of between-condition differences was evaluated by one-way repeated measures ANOVA (for multiple conditions) and paired t-test (for two groups), followed by a Bonferroni post hoc test to examine the multiple comparisons if there is a significance. $p < .05$ was considered statistically significant.

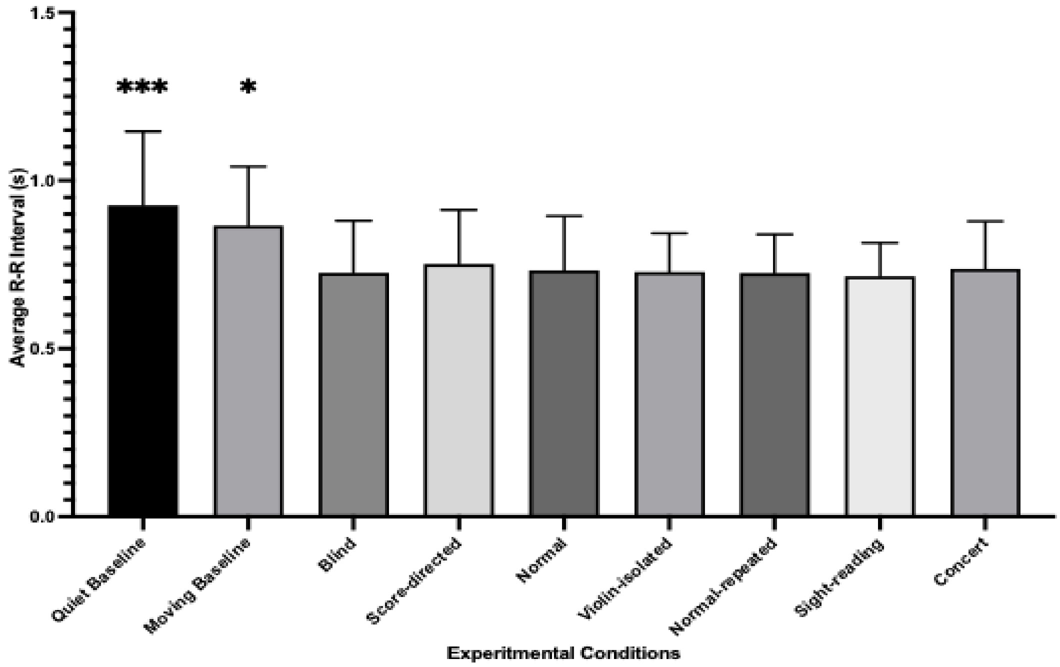
Chapter 4

Results

4.1 Heart Rate and Heart Rate Variability

To examine the variations in mean heart rate and heart rate variability in different experimental conditions. A one-way repeated measures ANOVA on average R-R interval and average SDNN was performed to distinguish the significance between repeated experimental conditions. The analysis demonstrated significant main effects between different conditions on DSQ's mean heart rate [$F(8, 24) = 12.26$, $p < .001$], shown in Figure 8. We used the Bonferroni method for multiple comparison corrections and found the average R-R interval in the Quiet Baseline ($p < .001$) and Moving Baseline ($p < .05$) are significantly higher than in all other conditions, which indicates a lower heart rate in the Quiet Baseline (mean R-R interval = 0.927 s) and Moving Baseline (mean R-R interval = 0.867 s). Besides, we did not observe any significance in BSQ's (Figure 9) average heart rate [$F(6, 18) = 2.518$, $p = 0.060$], and DSQ [$F(8, 24) = 1.269$, $p = .305$] (Figure 10) and BSQ's [$F(6, 18) = 2.353$, $p = .074$] (Figure 11) average heart rate variability between experimental conditions.

Figure 8.
Average R-R Interval of DSQ

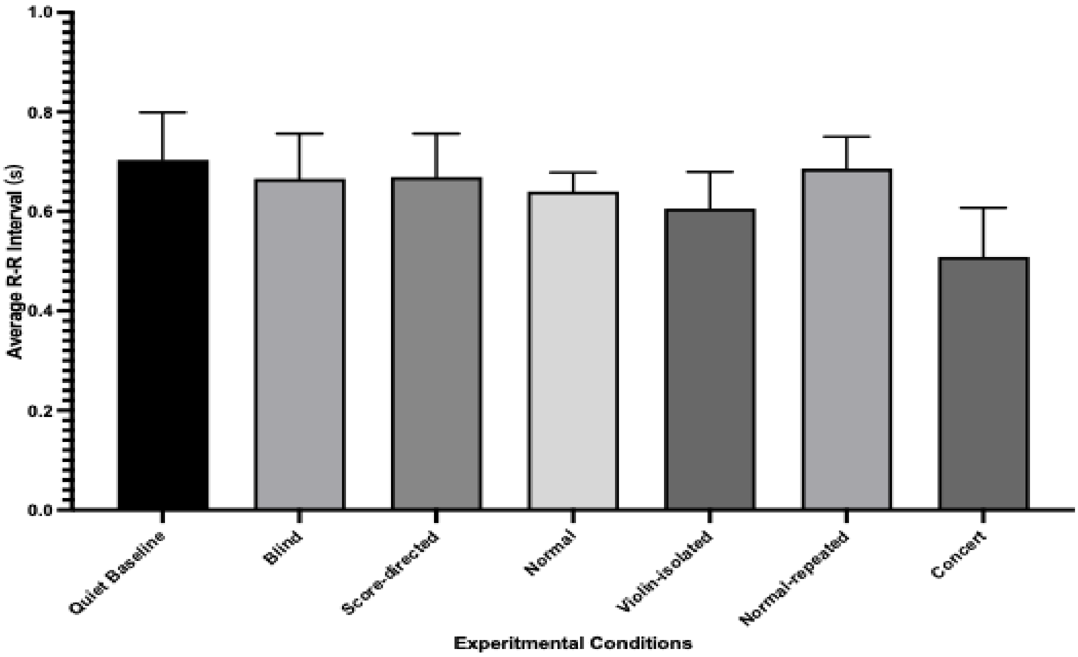


Note: *This chart was arranged based on the order of experimental conditions, the average R-R interval in the Quiet Baseline and Moving Baseline was significantly greater than in other conditions. *** p < .001 versus Blind to Concert conditions, * p < .05 versus Blind to Concert conditions. There was no significance between Quiet Baseline and Moving Baseline (p > .999).*

Table 4.
Average R-R interval of DSQ

Conditions	Mean R-R interval (s)	SD
Quiet Baseline	0.927044	0.21927
Moving Baseline	0.866515	0.17573
Blind	0.725589	0.155126
Score-directed	0.752019	0.160437
Normal	0.732709	0.161552
Violin-isolated	0.727886	0.115496
Normal-repeated	0.72481	0.11526
Sight-reading	0.715217	0.099882
Concert	0.73771	0.140633

Figure 9.
Average R-R interval of BSQ

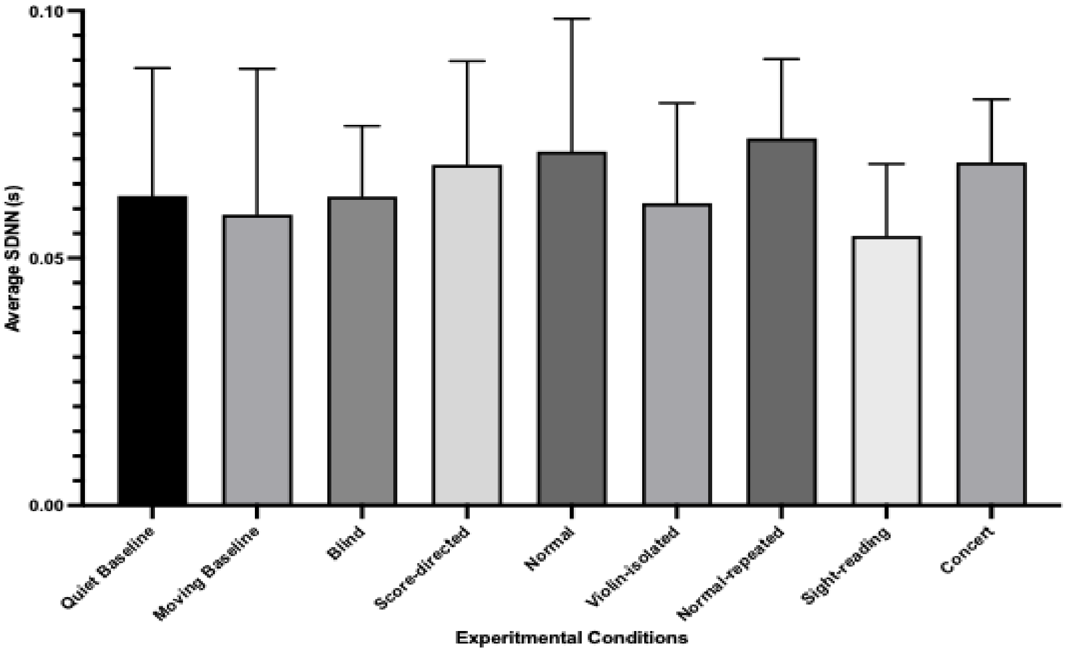


Note: *This chart was arranged based on the order of experimental conditions, except for the Normal-repeated condition, the data pattern was similar to the DSQ, but we did not observe any statistical significance between conditions.*

Table 5.
Average R-R interval of BSQ

Conditions	Mean R-R interval (s)	SD
Quiet Baseline	0.703133	0.095691
Blind	0.665655	0.090511
Score-directed	0.66885	0.087592
Normal	0.639761	0.038237
Violin-isolated	0.606114	0.073494
Normal-repeated	0.685809	0.064544
Concert	0.50889	0.098692

Figure 10.
Average SDNN of DSQ

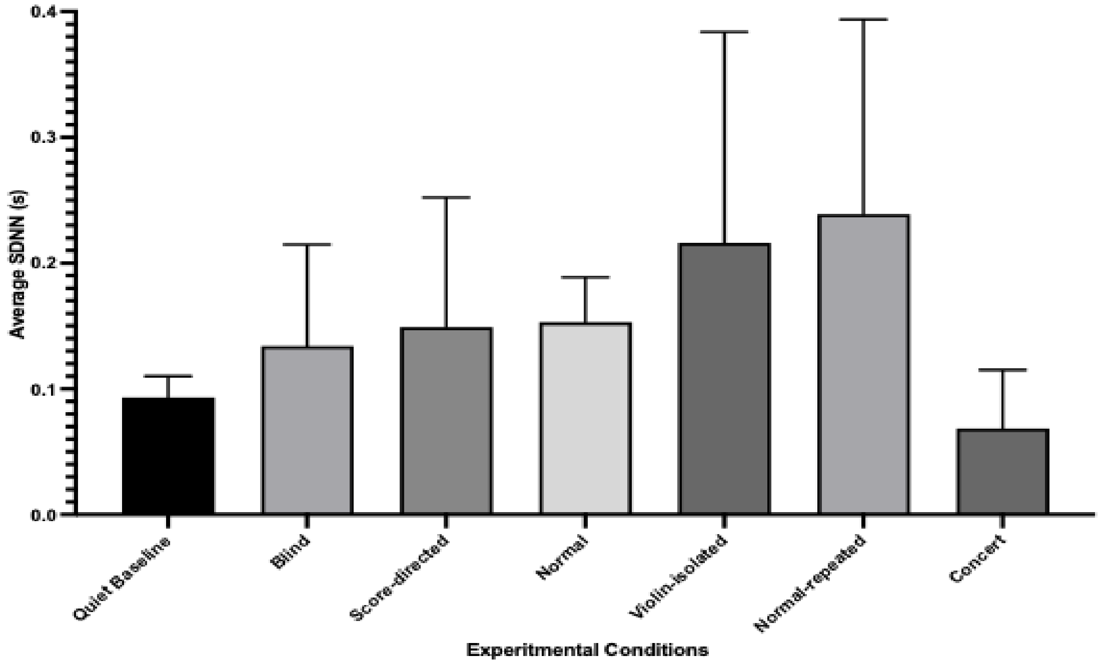


Note: This chart was arranged based on the order of experimental conditions, we did not observe any statistical significance between conditions.

Table 6.
Average SDNN of DSQ

Conditions	Mean SDNN (s)	SD
Quiet Baseline	0.062584	0.025855
Moving Baseline	0.058774	0.029468
Blind	0.062441	0.01427
Score-directed	0.068923	0.020907
Normal	0.071611	0.02682
Violin-isolated	0.061079	0.020231
Normal-repeated	0.074183	0.016057
Sight-reading	0.054513	0.014537
Concert	0.069318	0.012782

Figure 11.
Average SDNN of BSQ



Note: *This chart was arranged based on the order of experimental conditions, we did not observe any statistical significance between conditions.*

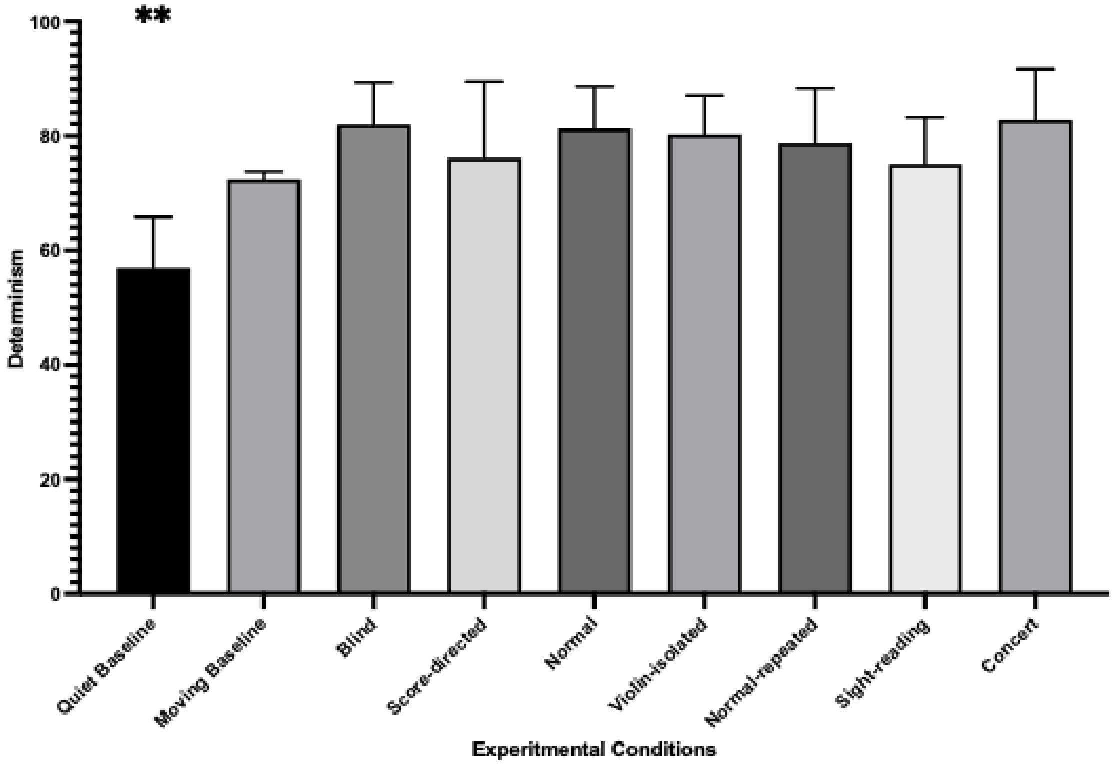
Table 7.
Average SDNN of BSQ

Conditions	Mean R-R interval (s)	SD
Quiet Baseline	0.093264	0.016949
Blind	0.134042	0.080636
Score-directed	0.14921	0.103064
Normal	0.153004	0.035836
Violin-isolated	0.216127	0.167579
Normal-repeated	0.23899	0.154786
Concert	0.068681	0.046401

4.2 Nonlinear Dynamics of Individuals' Cardiac Activity

Next, the RQA analysis of cardiac dynamics evaluates the predictability of individuals' cardiac patterns. A one-way repeated measures ANOVA was applied to identify whether average determinism (%DET) varied across conditions. We found both quartets have significance in different conditions. For DSQ [F (8, 24) = 9.114., $p < .001$] (Figure 12), and BSQ [F (6, 18) = 10.22, $p < .001$] (Figure 13). Through the same post hoc test, although the average %DET was not differing significantly between the musical performance conditions, both quartets demonstrated a significantly higher %DET in all musical performance conditions than in the Quiet Baseline (for DSQ, mean %DET in Quiet Baseline = 56.87, $p < .01$ versus Blind to Concert, $p < .05$ versus Moving Baseline; for BSQ, mean %DET in Quiet Baseline = 25.95, $p < .01$ versus Blind to Concert).

Figure 12.
Individuals' average %DET of DSQ

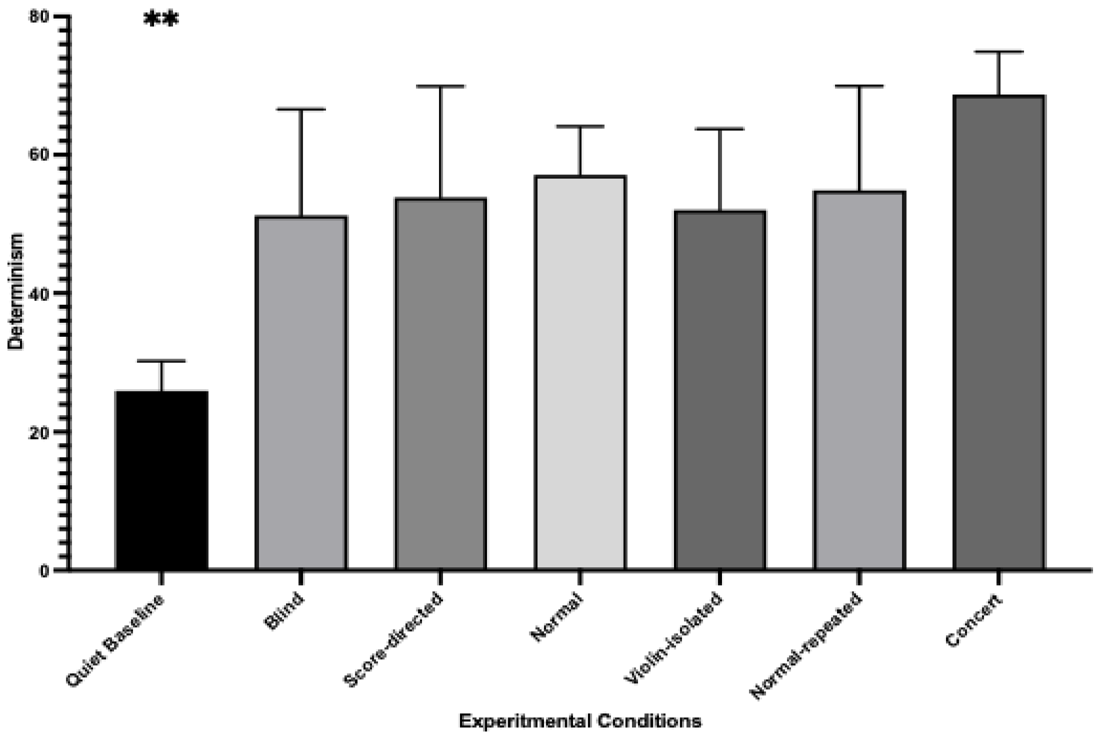


Note: *This chart was arranged based on the order of experimental conditions, the %DET in Quiet Baseline was substantially lower than in other conditions. ** p < .01 versus Blind to Concert conditions, and p < .05 versus Moving Baseline. Other conditions were not statistically significant.*

Table 8.
Individuals' average %DET of DSQ

Conditions	Mean DET%	SD
Quiet Baseline	56.87398	8.925736
Moving Baseline	72.33187	1.401937
Blind	81.93511	7.384667
Score-directed	76.13385	13.3346
Normal	81.25735	7.309075
Violin-isolated	80.27347	6.678795
Normal-repeated	78.70627	9.565746
Sight-reading	75.0579	8.104343
Concert	82.76427	8.891369

Figure 13.
Individuals' average %DET of BSQ



Note: *This chart was arranged based on the order of experimental conditions, the %DET in Quiet Baseline was substantially lower than in other conditions. ** p < .01 versus Blind to Concert conditions. Other conditions were not statistically significant.*

Table 9.
Individuals' average %DET of BSQ

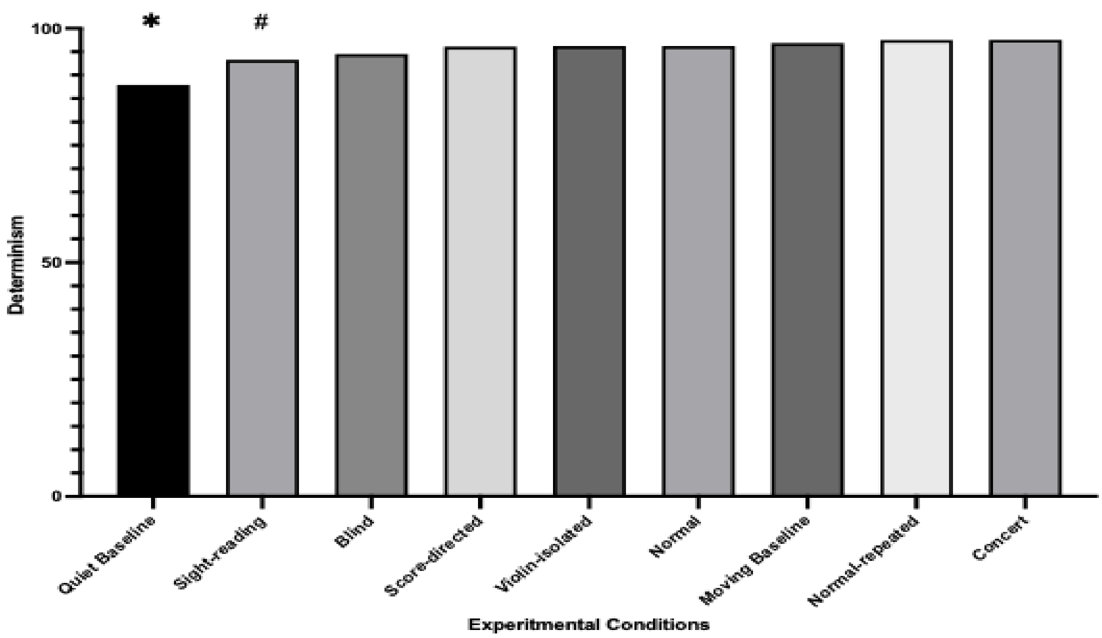
Conditions	Mean DET%	SD
Quiet Baseline	25.94595	4.229822
Blind	51.21758	15.35453
Score-directed	53.84826	16.08007
Normal	57.08539	7.045217
Violin-isolated	52.04206	11.68698
Normal-repeated	54.87587	15.05989
Concert	68.72337	6.194646

4.3 Group-level Cardiac Synchrony

4.3.1 Group-level Synchrony Comparison Between Conditions

To examine the synchrony level differences between experimental conditions, we tested the significance in %DET using the customized bootstrapping method mentioned in the methods chapter. For DSQ (Figure 14), we found that the %DET of the Quiet Baseline was significantly lower than all other conditions ($p < .05$), and the Sight-reading condition has significance with the Normal & Normal-repeated (95% CI of diff. [-7.2225, -0.8393], $p < .05$), and Concert conditions (95% CI to diff. [-7.6841, -1.6401], $p < .05$). For BSQ (Figure 15), results showed a similar pattern: Quiet Baseline was significantly lower than all other conditions ($p < .05$); Blind significantly different with Score-directed(95% CI of diff. [-18.8423, -3.0585], $p < .05$), Normal & Normal-repeated (95% CI of diff. [-23.7452, -7.845], $p < .05$), and Concert conditions (95% CI of diff. [-23.4837, -7.8552], $p < .05$); Violin-isolated differences with Score-directed (95% CI of diff. [-9.5319, -0.1164], $p < .05$), Normal & Normal-repeated (95% CI of diff. [-14.3449, -5.0125], $p < .05$), and Concert conditions(95% CI of diff. [-13.6896, -4.5715], $p < .05$); Score-directed have significance with Normal & Normal-repated (95% CI of diff. [-9.3984, -0.3089], $p < .05$) and Concert conditions (95% CI of diff. [-8.7439, -0.7618], $p < .05$).

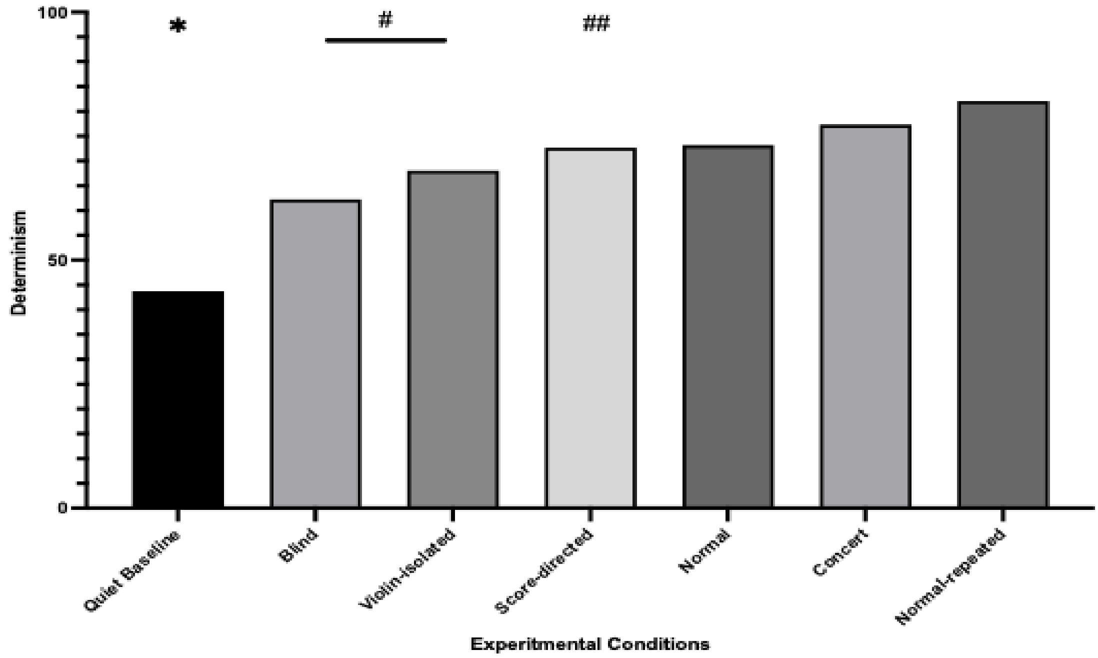
Figure 14.
Group-level synchrony rates of DSQ



Note: *The order of this chart was sorted from lowest to highest based on %DET values, which indicates the group-level synchrony rate. Quiet Baseline has the lowest DET% and Concert condition has the highest DET%. * p < .05 versus Sight-reading to Concert conditions, except for Moving Baseline. # p < .05 versus Blind to Concert conditions, except for Moving Baseline. Other conditions were not statistically significant.*

Figure 15.

Group-level synchrony rates of BSQ



Note: *The order of the chart was sorted from lowest to highest based on %DET values, which indicates the group-level synchrony rate. Results demonstrated a similar pattern to the results of DSQ, the Quiet Baseline was the lowest and the Normal-repeated was the highest. * p < .05 versus all other conditions. # p < .05 versus all other conditions, and there was no significance between Blind and Violin-isolated conditions. ## p < .05 significantly lower than Normal, Concert, and Normal-repeated conditions. There was no statistical significance between Normal, Concert, and Normal-repeated.*

Table 10.
Group-level synchrony rates of DSQ and BSQ

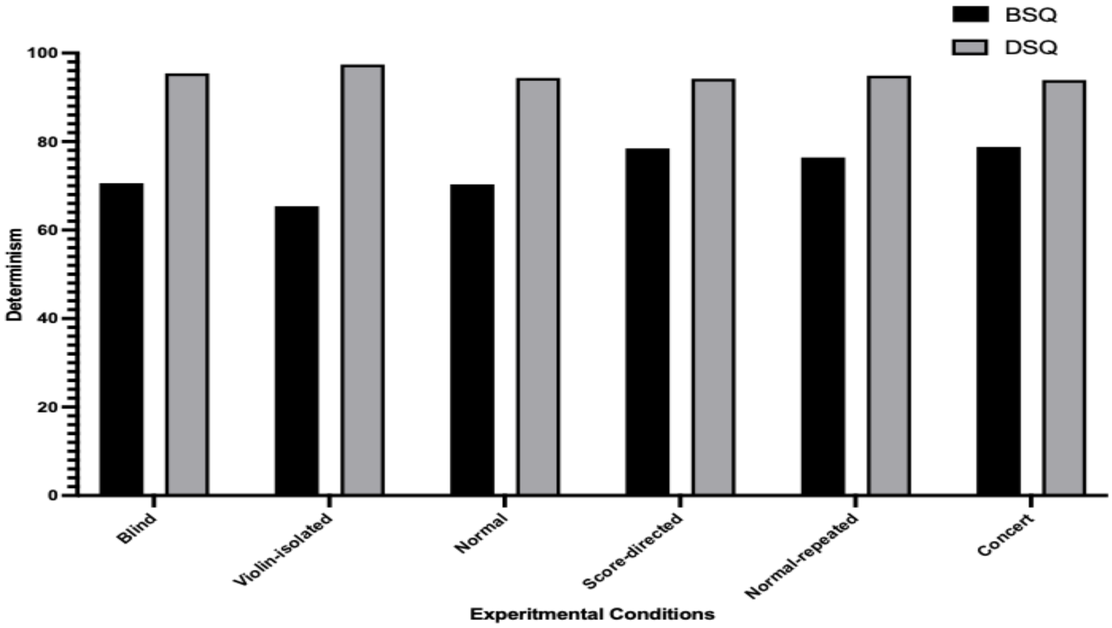
Conditions	DSQ (DET%)	BSQ (DET%)
Quiet Baseline	87.91349	43.75
Sight-reading	93.25356	NA
Blind	94.51318	62.19668
Score-directed	96.07635	72.68951
Violin-isolated	96.19182	68.06349
Normal	96.20209	73.20388
Moving Baseline	96.8254	NA
Normal-repeated	97.50831	82.08955
Concert	97.54098	77.3074

4.3.2 Group-level Synchrony Comparison Between Two Quartets

In addition, in the parallel comparison of group-level synchrony in six identical experimental conditions of DSQ and BSQ (Blind, Violin-isolated, Score-directed, Normal, Normal-repeated, Concert). We re-calculated the %DET in MdRQA based on consistent parameters and validated data by paired t-test between DSQ and BSQ (Figure 16). We found the average %DET of DSQ (mean = 95.0312) was substantially greater than BSQ (mean = 73.3227) [$t(5) = 8.193$, $p<.001$] (Figure 17).

Figure 16.

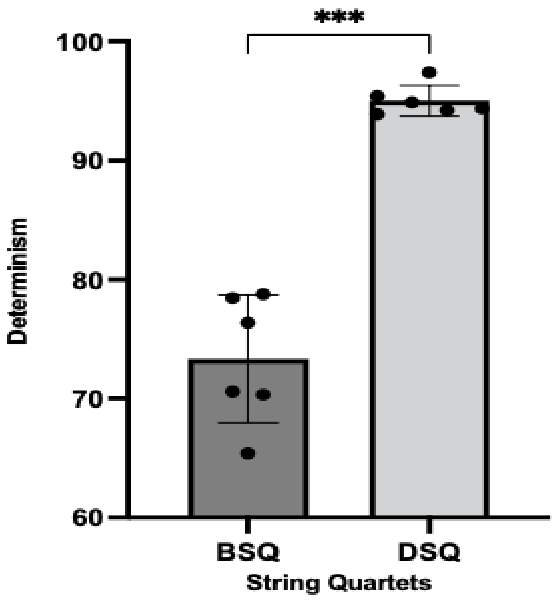
Comparison of group-level synchrony between DSQ and BSQ



Note: *This chart was sorted based on the order of experimental conditions. After re-calibrating the parameters for MdRQA of the comparison pairs, the DET% of DSQ was higher than the BSQ in every condition.*

Figure 17.

Comparison of the averaged group-level synchrony between DSQ and BSQ



Note: *This chart represents the average group-level synchrony between DSQ and BSQ in six identical conditions. The average DET% of DSQ was significantly greater than DET% of BSQ ($p < .001$).*

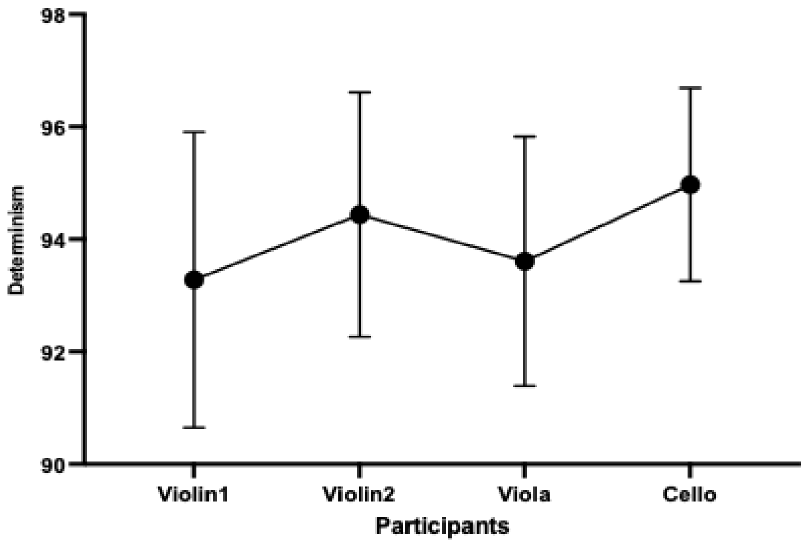
Table 11.
Comparison of group-level synchrony between DSQ and BSQ

Conditions	BSQ (DET%)	DSQ (DET%)
Blind	70.60459	95.40798
Violin-isolated	65.39263	97.4131
Normal	70.32569	94.37555
Score-directed	78.44171	94.21673
Normal-repeated	76.39077	94.88987
Concert	78.78687	93.88395
Mean	73.3237	95.0312

4.3.3 Averaged Individual Dyadic Synchrony

Lastly, to examine the individual contribution to the group-level synchrony, a one-way repeated measures ANOVA was applied to averaged individual dyadic synchrony between musicians. Not surprisingly, we did not observe any significance between the musicians' individual contribution to the group-level of synchrony in both DSQ [$F(3, 21) = 2.321$, $p = .104$] and BSQ [$F(3, 15) = 0.6088$, $p = .620$].

Figure 18.
Mean of the averaged individual dyadic synchrony of DSQ



Note: This figure shows the individual synchrony contribution of the four musicians in DSQ across the eight performance conditions (excluded Quiet Baseline), with Cello being the highest and Violin1 being the lowest, but without any statistical significance between the four musicians (p = .104).

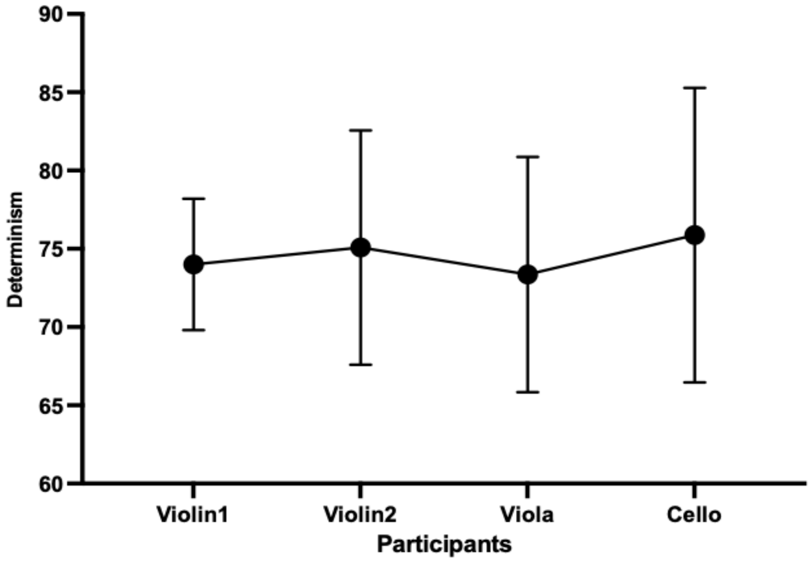
Table 12.

Averaged individual dyadic synchrony of DSQ (in DET%)

Conditions	Violin1	Violin2	Viola	Cello
Moving Baseline	88.01767	92.12311	90.1578	97.05369
Blind	93.63686	92.56929	93.9644	95.69892
Score-directed	94.03227	95.16667	93.50789	94.15352
Normal	94.47904	96.36808	94.39982	95.69633
Violin-isolated	93.23434	95.02893	93.46733	94.02429
Normal-repeated	95.91946	97.21244	96.38773	95.86903
Sight-reading	91.05588	91.25768	90.84253	91.47192
Concert	95.85766	95.7646	96.13493	95.80166
Mean	93.2791	94.4363	93.6078	94.9711

Figure 19.

Mean of the averaged individual dyadic synchrony of BSQ



Note: This figure shows the individual synchrony contribution of the four musicians in BSQ across the six performance conditions (excluded Quiet Baseline), with Cello being the highest and Viola being the lowest, but without any statistical significance between the four musicians (p = .620).

Table 13.
Averaged individual dyadic synchrony of BSQ (in DET%)

Conditions	Violin1	Violin2	Viola	Cello
Blind	67.0635577	65.5409602	64.296904	64.3717517
Score-directed	76.2058313	78.8883114	76.9604418	80.9942133
Normal	77.7713239	71.9272776	78.0071941	79.7840322
Violin-isolated	71.0536421	69.1334036	63.5586079	63.3985611
Normal-repeated	77.4387729	79.382244	81.2435141	84.049989
Concert	74.4736214	85.5870887	76.0724827	82.622772
Mean	74.0011	75.0765	73.3565	75.8702

Chapter 5

Discussion

The main objective of this thesis was to examine the musicians' cardiac dynamics and synchrony in string quartet performances, to expand our understanding of physiological responses and synchronization in the musical ensemble. In this master's thesis, we presented cardiac data from two string quartets performing under different experimental conditions. In addition to the conventional linear analysis of heart rate and heart rate variability, we introduced nonlinear methods - RQA and MdRQA to analyze the predictability of individuals' cardiac rhythms as well as the cardiac synchrony in quartets.

In this chapter, we will summarize findings from these analyses according to the research questions raised in chapter 1, followed by a general conclusion. In the last part, we will reflect on the limitations of the presented findings and suggest possible directions for future work.

5.1 Answer to RQ1

How do the cardiac dynamics change during the musical performance in different experimental conditions?

We investigated cardiac activity from two aspects. The linear analysis showed that DSQ's average heart rate during musical performances was significantly higher than Quiet Baseline and Moving Baseline. However, there was no significant difference between the different adverse conditions. Moreover, we did not observe substantial differences in BSQ's average heart rate and average SDNN in both quartets between different conditions. These results are partially in contrast to previous studies that have shown higher heart rate and lower heart rate variability during musical performances (Brotons, 1994; de Manzano et al., 2010; Harmat et al., 2011; LeBlanc et al., 1997; Vellers et al., 2015; Wright & Palmer, 2020). We believe a major issue for this is that the sample size of the present study is limited, two groups of data may not reflect sufficient statistical validity. Besides, our study is the first study to examine musicians' heart rate and heart rate variability in musical ensembles, whether performing together affects heart rate and heart rate variability is still unknown, which may require further studies to explore.

Furthermore, we likewise saw no evidence that when musicians playing unfamiliar music would cause an increase in heart rate and decrease in heart rate variability, which was inconsistent with the findings of Harmat et al. (2011). Since the Sight-reading condition was only performed in the DSQ's experiment, in addition to the possible reason that the sample size was too small, we speculate that for well-known experts like DSQ, the repertoire was not difficult enough to elevate their anxiety levels and therefore did not reflect significant differences in heart rate and heart rate variability.

The nonlinear analysis employed RQA to examine individuals' cardiac dynamics. Similar to the study conducted by Wright and Palmer (2020), both quartets demonstrated more predictable cardiac dynamics during musical performances compared to the resting baseline. These findings further support that musical activity can promote the predictability of heart activity in a general way, and indicated the effectiveness of the nonlinear approach in examining variations in physiological responses during musical activity. Moreover, we did not observe any significant differences or patterns in the individuals' DET% in adverse conditions of both quartets. This phenomenon is inconsistent with Wright and Palmer's (2020) speculation that the predictability of the cardiac patterns may be associated with behavioral difficulty. Hence, more studies are needed to address the relationship between nonlinear cardiac dynamics, behaviors, and cognitive effort.

5.2 Answer to RQ2

What is the relationship of cardiac dynamics between the collaborators of the string quartet? Does synchronization occur when they perform together?

We applied MdRQA to investigate the group-level cardiac synchrony as well as the individual contribution to the group-level synchrony for both quartets. Results showed that the two quartets exhibited similar patterns in group-level cardiac synchrony. Consistent with our expectations, the DSQ and BSQ's synchrony levels of the Quiet Baseline were significantly lower than all other performance conditions. Consequently, this result suggests that playing in the string quartet can promote the cardiac synchrony level, which was highly correlated with previous conclusions that singing or listening to music together can increase cardiac synchrony (N. F. Bernardi et al., 2017; Müller & Lindenberger, 2011; Ruiz-Blais et al., 2020; Vickhoff et al., 2013). Therefore, we suggest that the level of cardiac synchrony in musical ensembles may not only be attributed to respiratory control, but similar to the physiological synchrony in other social activities, which may serve as a physiological marker of the interpersonal synchrony level, influenced by shared emotions and experiences.

In addition, in the experiment of BSQ, the group-level synchrony in the Blind and Violin-isolated conditions was significantly lower than in the Score-directed, Normal, Normal-repeated, and Concert conditions. Furthermore, the Score-directed condition was also lower than the Normal, Normal-repeated, and Concert conditions. These results also coincided with our expectation that communication constraints negatively affect the musicians' cardiac coupling, and the extent of the effect is correlated with the degree of obstruction. Moreover, results showed that the cardiac synchrony rate of DSQ decreased significantly only during the Sight-reading condition, which may indicate that playing unfamiliar pieces together affects the level of cardiac synchrony.

Finally, we did not observe any statistical significance in the averaged individual dyadic synchrony for musicians in both quartets. Even in the Violin-isolated condition, where the first violin, as the quartet leader was separated, we still did not find any significant change in the individual synchrony rate. Hence, this result further supports that the cardiac synchrony may be a sign of shared music experience which may tend to be affected as a whole rather than multiple individuals.

5.3 Answer to RQ3

What is the difference between the cardiac dynamics of the Danish String Quartet and the Borealis String Quartet?

As discussed in the previous section, the BSQ was more influenced by adverse conditions. The group-level cardiac synchrony rate decreased in the Blind, Violin-isolated, and Score-directed conditions relative to the undisturbed performance conditions such as Normal and Concert. The DSQ, on the other hand, was not significantly affected by the various communication constraints. Moreover, the synchrony rate of DSQ was significantly greater than BSQ in every identical experimental condition. Although the two experiments were conducted at different times and places, we still tentatively believe that the difference in cardiac synchrony rate may be mainly due to the differences in the level of expertise. Since previous studies have addressed that highly skilled musicians are better to execute and synchronize their motion with time (Aoki et al., 2005; Brown et al., 2015; Furuya & Kinoshita, 2007, 2008; Palmer, 1997), which may allow DSQ to be less affected by adverse conditions. Besides, in an informal conversation with DSQ after the experiment, musicians also reported that since they had been practicing and performing together for long enough, they felt no difference when they could not see each other or sit differently. Therefore, we cautiously conclude that cardiac synchrony level in the musical ensemble may be related to the level of expertise. Experts may have a higher cardiac coupling rate when they play together in an ensemble.

5.4 Conclusion

In this thesis, we demonstrated the cardiac dynamics of two string quartets performing in multiple experimental conditions. Our findings proposed that performing in a quartet promotes more predictable cardiac dynamics and group synchrony. Different constraints may affect the group-level synchrony to the extent that may be related to the level of expertise. To our knowledge, this thesis is the first study using both linear and nonlinear methods to examine the cardiac dynamics and synchrony in string quartet performances. We also provided the first evidence that playing in the quartet facilitates cardiac activity synchronization.

5.5 Limitations and Future Work

In contrast to previous similar studies, the present study adopted a more ecological approach to the experiment rather than a strict laboratory setting, as we were more interested in musicians' reactions to real-life performances as well as it was impractical to recruit dozens of string quartets for a repeat experiment. The advantage of our approach is that we were given a unique opportunity to work with and collect physiological data from some of the best musicians in the world. While the inevitable limitations were that we struggled to control the experiment's variables in a semi-open space as well as limited statistical power due to the small sample size. Hence, we would like to emphasize again that we are cautious about generalizing the conclusions of our study.

Furthermore, in addition to cardiac activity measurement, musicians also wore motion capture suits with markers and eye-tracking glasses during experiments, which potentially made musicians uncomfortable and more difficult to perform, thus impacting the measured cardiac dynamics. Therefore, future experiments could only focus on the measurement of vagal signals, such as respiration, skin conductivity, and blood pressure, to systematically study physiological rhythms in a minimally intrusive manner.

Besides, the current results were also limited by our selection of the music excerpts, as both string quartets played the same, relatively short classical music excerpt (68 bars). It would be helpful to explore the effects of musical rhythms, musical genres, or different levels of musical expressions on physiological dynamics and coupling.

Another limitation of this study was that the experimental design included only a small fraction of the factors pertaining to visual communication constraints. It also seems wise to examine the role of auditory feedback, individual differences, and the effect of circadian rhythms on cardiac synchrony in musical ensembles. Moreover, it will be interesting to explore the relationship between physiological synchrony, motor synchrony, and neural entrainment, which will help us to further understand the reasons and mechanisms of interpersonal synchronization in group activities.

In the future, laboratory studies of physiological dynamics and synchrony in musical ensembles will be valuable. To examine the physiological rhythms in a more rigorous setting by designing more efficiently replicated experiments, such as recruiting piano duets instead of string quartets. In conclusion, compared with similar topics such as sensorimotor synchronization and neural entrainment, we still understand very little about the physiological dynamics and synchrony in musical ensembles, many more studies are needed.

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Appendix A

Analysis scripts

A Github repository includes the MATLAB and Python scripts coded for this study available on: https://github.com/wenboyi/CardiacDynamics.git

Appendix B

Music Score

The 68 bars of Haydn's *Op.76, No.4, in B-flat Major* played by the Borealis String Quartet and Danish String Quartet in experiments, downloaded from the public domain.

Op. 76, No. 4, in B-flat Major ("Sunrise")


20
cen - do
f
fz
ff
30


40


50
f
60
tr
p


ff
ff
ff
ff