Development of a home-based biofeedback system

-posture-respiration and heartrate-music feedback system

（住居内向けバイオフィードバックシステムの開発ー姿勢ー呼吸および心拍数ー音楽フィードバックシステム）

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ABSTRACT

As the awareness of health and wellness grows, more people are emphasizing their well-being and exploring ways to maintain and enhance their health from the comfort of their homes. The integration of biofeedback training with technology represents a pivotal advancement in personal health management, yielding substantial benefits for both mental and physical well-being. The motivation of this study is to emphasize the importance of seamlessly incorporating biofeedback technologies and devices into domestic settings without imposing undue cognitive demands or effort. To address this motivation, three comprehensive studies were conducted.

In the first study, a respiration-posture feedback system was developed. An experiment investigated the impact of various lifting heights (0.5 cm, 1 cm, 3 cm, and 6 cm) on respiration. Results revealed a significant increase in Respiration Interval (RI) for the 1 cm, 3 cm, and 6 cm conditions compared to the 0.5 cm condition. The heart rate (HR) recorded during the 1 cm intervention was significantly lower than in the 0.5 cm condition. The high-frequency (HF) component of heart rate variability (HRV) in the 0.5 cm condition exhibited a significant decrease compared to the 3 cm and 6 cm conditions. The increase in alpha wave components at the 1 cm condition surpassed that of the 3 cm and 6 cm conditions. These findings demonstrate the efficacy of the respiration-posture feedback system in regulating respiration and enhancing cardiac parasympathetic nervous system activity, which was remarkable in the 1cm condition.

In the second study, a heart rate-based music feedback system was developed to dynamically adjust the tempo of a music track to match the user's HR in real time. Two conditions, Feedback (FB) and constant (CT), were experimentally compared. Significant differences were observed between conditions in the RI, HF component of HRV, and beta power of brain waves. Furthermore, subjective scores and impressions for musical tracks exhibited no significant differences. These results imply that physiological responses diverged between conditions due to underlying physiological functioning at an unconscious level rather than perceptible or recognizable differences in music.

In the third study, a new method for human pulse measurement using consumer

earphones and headphones was proposed. The feasibility evaluation demonstrated accurate pulse peak measurement using earphones/headphones. The frequency characteristics of audio devices at the frequency of interest aligned with the center frequency of the HR, facilitating the reproduction of the original, non-distorted pulse waveform, was estimated.

In conclusion, the triad of studies conducted within this research endeavor converges to underscore the profound potential of seamlessly integrating biofeedback technologies into domestic settings, as outlined in the initial motivation. The observed impact, particularly evident in the 1cm condition, underscores the potential of the respiration-posture feedback system as a consumer product aimed at promoting deep breathing without requiring conscious user attention. The heart rate-based music feedback system highlights the system's ability to influence psychophysiological states at an unconscious level. Users can easily use the system at home to achieve effects that affect their physiological and psychological states without having to understand the system itself. The third study pioneers a method for human pulse measurement through consumer earphones and headphones has no device restrictions and can be used at home. HR can be monitored while listening to music to provide users with convenient and timely health monitoring services. The contribution made lies not only in the individual advancements of each study but in the collective establishment of biofeedback systems as practical tools for enhancing personal health management in domestic environments. These findings provide methods and theories for enhancing health and well-being in the home environment.

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CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Health promotion with/without using technology

According to the World Health Organization (WHO), health is a complete state of physical, mental, and social well-being, and not merely the absence of disease or infirmity [1]. Maintaining good health enables individuals to perform daily activities with ease and efficiency. It empowers them with the vitality to actively engage in work, leisure, and social interactions. Optimal health leads to increased productivity[2], enabling significant contributions to society. This outcome has a positive impact on the economy[3] and contributes to the reduction of healthcare expenses[4].

However, as the pace of contemporary society quickens, the mounting pressures encountered in our daily routines have given rise to notable health challenges[5,6]. Addressing these health challenges requires a multifaceted approach. This encompasses not only medical interventions but also lifestyle modifications, mental health support, and societal initiatives aimed at reducing stressors and promoting overall well-being.

Sleep plays an important role in maintaining and improving physical and mental health[7]. Insufficient or poor-quality sleep affects approximately 40 to 50% of the global population [8]. This not only leads to chronic fatigue but also contributes to a host of secondary health issues. Obstructive Sleep Apnea (OSA) is the most common sleep-related breathing disorder and is highly prevalent, potentially affecting as many as one billion people worldwide [9]. It leads to disrupted sleep patterns and can result in daytime drowsiness and diminished cognitive function, further exacerbating the challenges individuals face in their daily lives [10,11].

Complementary and Alternative Medicine (CAM) refers to medical practices or treatments that fall outside the realm of conventional medicine[12]. In the past, alternative medicine have been employed to maintain and improve health. Acupuncture, originating from ancient China, involves the precise insertion of fine needles into specific points to regulate energy flow and promote overall health. The research findings suggest that acupuncture holds potential in alleviating primary depression[13], mitigating chronic headaches[14], and providing relief from postoperative[15] and chronic pain[16]. Massage therapy is an ancient healing method used for health care, disease prevention[17], and clinical studies show that massage therapy can have a positive impact on pain, anxiety, and muscle tension[18]. Humans have employed herbal medicine for the treatment of illnesses since the dawn of civilization[19]. This ancient practice involved utilizing different parts of plants to formulate remedies aimed at alleviating a wide array of ailments and promoting overall well-being[20]. The practice of yoga, originating in ancient India, incorporated breath control, postures, and meditation to foster physical, mental, and spiritual equilibrium[21-23]. Tai Chi is a traditional Chinese practice encompassing both physical and mental exercises. Research has substantiated that engaging in Tai Chi can augment balance, enhance gait, and improve muscle strength[24,25]. Moreover, utilizing Tai Chi as an intervention yields a favorable influence on depression, anxiety, and overall stress management[26].

With the rapid advancement of technology, significant breakthroughs have been achieved in the fields of medicine and health. Advanced medical equipment and treatment methods have enabled the control and even eradication of many diseases, extending human lifespan and improving quality of life. One significant advancement is the advent of telemedicine, which leverages digital communication technologies to facilitate remote consultations between healthcare professionals and patients[27]. This approach not only improves access to healthcare services, particularly for individuals in underserved or remote areas, but also reduces the need for physical visits, minimizing logistical challenges and wait times [28-30]. Moreover, the integration of health monitoring equipment enables individuals to monitor vital health metrics in real time[31]. Contributes to early detection of disease and monitoring of disease development and treatment[32]. Virtual medical technologies have also emerged as a powerful tool in modern healthcare. Advanced simulations, augmented reality, and virtual reality (VR) applications are increasingly used in medical training, surgical planning[33], and therapy sessions[34]. These technologies provide healthcare professionals with immersive, hands-on experiences that enhance their skills and improve patient care outcomes[35]. In addition, data analytics and artificial intelligence are driving innovations in diagnostics, treatment planning, and personalized medicine. These technologies leverage vast amounts of health data to identify patterns, make predictions, and offer tailored treatment options, ultimately leading to more effective and efficient healthcare interventions[36,37].

The integration of technology into health promotion endeavors presents both opportunities and challenges. While digital platforms have the potential to bridge gaps in access and equity, the digital divide persists, with certain populations lacking access to technology or internet connectivity. Moreover, the proliferation of health information online has led to an abundance of misinformation, making it difficult for individuals to discern credible sources. Personalization and tailoring of interventions are made possible through algorithms and data tracking, but privacy concerns and algorithmic biases must be carefully addressed to ensure effectiveness and acceptability.

1.1.2 Maintaining and Enhancing Health in Daily Life

There is a growing interest in maintaining and enhancing wellness in everyday life, contributing to improved physical health, enhanced mental health and an overall improved quality of life for individuals.

A healthy body lays the foundation for daily well-being and enables a more active and fulfilling life. Scientific research has consistently shown that a combination of regular physical exercise [38], a balanced and nutritious diet[39], adequate and quality sleep[40,41], avoidance of detrimental habits(cigarettes and alcohol) [42-44], consistent access to healthcare, and adherence to routine preventive check-ups are essential for maintaining and enhancing health in daily life.

Mental health holds equal significance. Studies have demonstrated that maintaining a positive mental outlook can enhance the immune system, lower the risk of chronic diseases, and potentially extend lifespan[45,46]. Studies in psychology propose that diaphragmatic breathing may induce relaxation responses, benefiting both physical and mental health[47]. A study proposes that participating in social activities enhances overall quality of life[48]. Aneeque Jamil et al. (2023) revealed that the positive emotions induced by meditation can effectively alleviate various mental health issues, such as social anxiety disorder, post-traumatic stress disorder

(PTSD), anxiety, and depression [49]. Studies have demonstrated that listening to music has a calming effect and can assist in reducing stress levels [50]. Norma Daykin et al. (2018) offered evidence supporting the positive influence of music and singing on the well-being of adults[51]. Research indicates that regular physical activity can significantly enhance psychological well-being and alleviate symptoms of depression, anxiety, and stress [52]. Participating in Tai Chi is likely to confer benefits such as improved flexibility, reduced depressive symptoms, lower anxiety levels, and heightened interpersonal sensitivity[53-56]. Numerous studies demonstrate that deep breathing positively affects factors including stress, anxiety, and negative mood[57-60].

1.1.3 Technological interventions

Technological interventions also play a pivotal role in maintaining and enhancing health in various ways. Mobile health is considered a technological intervention in the field of healthcare [61]. Through the use of applications on smartphones and tablets, can be accessed and transmitted efficiently[62-64]. Individuals utilizing Wearable Health Devices (WHD) can benefit from comprehensive health and safety monitoring, effective chronic disease management, accurate disease diagnosis and treatment, as well as rehabilitation[65,66].

WHDs are now commonly employed to monitor daily physical activities and personal health status, providing easy access to metrics such as HR, body temperature, blood pressure, and blood glucose levels [67]. Existing wearable devices have been engineered for application across various anatomical regions of the human body, broadly categorized into three groups: head-worn, limb-worn, and torso-worn devices [68]. Table 1 provides an overview of wearable health devices available on the market. Timely access to patients' physiological data aids doctors in monitoring their risk profile, enabling prompt medical interventions, which in turn contributes to reducing mortality rates [69]. Additionally, it facilitates individuals in meticulously tracking and overseeing their exercise routines, nutritional intake [70], medication adherence [71], and other health-related behaviors[72].

Table 1: Overview of wearable health devices on the market

Position	Device Name	Type	Brand	Main Features
Head	Muse 2[73]	EEG Headband	Muse	Meditation training, EEG monitoring, breath training, heart rate monitoring
	Vuzix M400[74]	Smart Glasses	Vuzix	Teleconferencing, Operations, Telemedicine
	Joule[75]	Earring Backings	Joule	Heart Rate monitoring, Calories Burned, Activity Level
	Headband[76]	SmartSleep Headband	Philips	Improve sleep
Limb	ŌURA's Oura Ring[77]	Smart Ring	ŌURA	Heart rate, HRV, motion, and temperature heart monitoring, etc.
	Fitbit sense2[78]	Smartwatch	Fitbit	SpO_2, ECG, relax breathing sessions, sleeping tracking, skin temperature
	Apple Watch Series 9[79]	Smartwatch	Apple	ECG, SpO_2, sleep tracking, fitness monitoring
	Blood pressure watch[80]	Smartwatch	Xiaomi	Blood pressure monitoring, ECG, fitness features
	Micoach Speed Cell[81]	Fitness Tracker	Adidas	collects performance data, assist players in training
Torso	Nadi X Yoga Pants[82]	Smart Clothing	Wearable X	Sense when your yoga pose needs refining
	Hexoskin Pro Kit[83]	Smart Clothing	Hexoskin	Measures Heart rate, respiration, activity levels, sleep tracking
	Smart clothing jacket[84]	Smart Clothing	Levi's X Google	Answer calls, play music, take photos
	Smart shirt[85]	Smart Clothing	Ambiotex	Measures heart rate, anaerobic info, and stress levels

1.1.4 Biofeedback

Biofeedback can be defined as the process that enables individuals to consciously alter their physiological activities[86]. Biofeedback emerged as a distinct field of study during the 1960s, and in subsequent decades, it has gained prominence as a complementary or alternative therapeutic approach for addressing various clinical conditions and mitigating symptoms[87]. The groundwork for biofeedback research is believed to have been established in the 1930s through the introduction of progressive relaxation techniques [88] and autogenic training [89]. Autogenic training, a relaxation technique devised by the German psychiatrist Johannes Heinrich Schultz and initially documented in 1932, entails daily practice sessions lasting approximately 15 minutes, typically conducted in the morning, midday, and evening. This method has demonstrated efficacy in alleviating symptoms of stress. The incorporation of information concerning mental and physical states, gathered through electronic sensors during these practices, later became fundamental to the development of biofeedback [89]. In recent decades, the field of healthcare and psychological interventions has witnessed a surge of interest in biofeedback techniques. Biofeedback uses instruments to measure a patient's physiological responses and provide real-time feedback to help the patient learn to change those responses. Biofeedback involves measuring physiological parameters in real time, allowing individuals to enhance awareness of how their actions, thoughts, and emotions impact their organism, the aim is to foster greater control over these physiological parameters[90].

The general architecture of a biofeedback system is illustrated in Figure 1. Sensors detect physiological signals from the participant, such as heart rate, muscle tension, skin conductance, or brain waves. Once the physiological signals are captured by the sensors, they are processed by a signal processing unit. Next, the processed physiological signals are conveyed to an actuator. The actuator is responsible for delivering feedback to the participant based on the analyzed physiological data. In a conventional biofeedback system, feedback is presented to the user through dedicated displays or interfaces. Ambient biofeedback systems integrate feedback into the user's environment, feedback may be presented through elements of the user's surroundings, such as lighting, soundscapes, or environmental cues. Additionally, participant may need a dedicated time and location for traditional biofeedback training sessions. Ambient biofeedback systems are designed to seamlessly integrate into the participant's environment and daily activities. They may utilize wearable devices, smart home technologies, or other connected devices to provide feedback in real-time without requiring the participant to actively engage with dedicated biofeedback equipment.

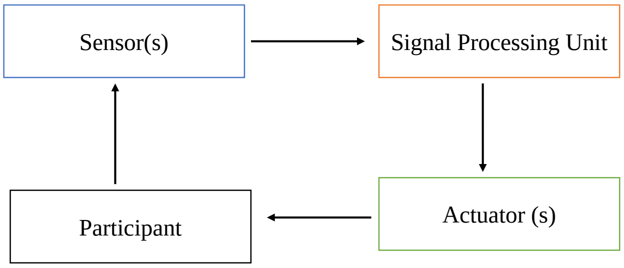


Figure1: Architecture of a biofeedback system.

Table 2: Types of Biofeedback and Descriptions.

Type of Biofeedback:	Description
Electromyography (EMG)	Measures muscle activity and tension[91]
Electroencephalography (EEG)	Monitors brainwave patterns[92]
Electrodermal activity (EDA)	Measures electrical conductance of the skin[93]
HRV	Analyzes variations in the time interval between heartbeats[94]
Respiratory Biofeedback	Focuses on controlling and regulating breathing patterns[95]
Blood Pressure Biofeedback	Helps regulate blood pressure levels[96]
Multi-Modal Biofeedback	Combination of two or more biofeedback[97]

Table 2 illustrates various types of biofeedback, including breathing, brain waves, HR, muscle activity, sweat gland activity, and temperature, among others. EMG Biofeedback, muscle tension is positively correlated with the degree of emotion, and the skeletal muscles of the forehead are the most representative[91]. For anxiety, tension, and insomnia generally do relaxation training that inhibits myoelectricity[98]. EDA Biofeedback, during emotional stimulation, the eccrine glands are activated, leading to the production of sweat, which serves as an efficient conductor of electrical current. Consequently, the electrical properties of the skin undergo changes. The degree of emotional arousal correlates with the amount of sweat secreted, resulting in a proportional alteration in the skin's electrical properties[99]. Respiratory Biofeedback, respiratory rate is one of the important parameters, and low-frequency respiratory exercises have long been recognized as beneficial to physical and mental health[100].

EMG-biofeedback can be defined as a technique that utilizes specialized equipment to provide individuals with visual and audible signals, offering insights into their internal physiological events, both normal and abnormal[101,102]. The primary purpose is to educate individuals on how to voluntarily control and manipulate these otherwise involuntary or imperceptible physiological events by actively engaging with and manipulating the signals displayed by the equipment[103]. The intensity of emotional experiences is often positively associated with muscle tension, with the muscles in the forehead serving as a notable representation of this correlation[104]. This relationship has paved the way for utilizing muscle tension as a therapeutic intervention for addressing a spectrum of conditions such as stress, insomnia, anxiety, and certain psychosomatic disorders. Study shows facial muscle activity is closely related to differences in emotional valence[105]. A study assessed the immediate impacts of facial EMG-based biofeedback on enhancing facial expression and emotion recognition, essential components of nonverbal social communication skills in Parkinson's disease patients. The group undergoing facial EMG biofeedback demonstrated notable enhancements in overall facial expressions, particularly in the domains of happiness and disgust[106]. Additionally, EMG-biofeedback has been shown to be beneficial in the recovery process from knee osteoarthritis[107]. Rehabilitation treatments for paralyzed patients often involve electromyography enhancement training, facilitating gradual restoration of motor function and heightened awareness in affected individuals[108].

Neurofeedback, a specialized form of biofeedback, empowers individuals to gain self-regulation over brain functions by monitoring and providing feedback on brain waves[109]. This technique involves the recording of EEG during neurofeedback sessions. Neurofeedback therapy monitors the brain's brain wave activity and provides feedback almost immediately, usually through visual or audio cues[110]. The distinct frequency components of brain waves are categorized into delta (less than 4 Hz), theta (4–8 Hz), alpha (8–13 Hz) (alpha waves are often associated with alertness and relaxation[111]), beta (13–30 Hz), and gamma (30–100 Hz)[109]. Each component corresponds to a specific physiological function. There are different neurofeedback training methods for different brainwave frequencies. In their neurofeedback training study, Nan et al. (2015) demonstrated that increasing the relative amplitude of individual alpha bands significantly enhances short-term memory[112]. Angelakis et al. (2015) demonstrated in their EEG peak alpha frequency neurofeedback training study an improvement in cognitive processing speed and executive function[113]. Neurofeedback training aimed at enhancing the low-beta component sensorimotor rhythms (12-15 Hz) and beta 1 (15-18 Hz) has been shown to improve attention[114]. Another neurofeedback study used closed-eyes auditory feedback to increase the ratio of theta to alpha waves, leading to professionally significant enhancements in music and dance performance and mood[115]. Additionally, enhanced gamma band activity allows for more flexible processing of integrated information in short- and long-term memory[116].

The evidence and protocols for the application of biofeedback have undergone extensive scrutiny in medical journals, particularly in conditions such as chronic headaches[117], pain management[118], hypertension[119], as well as mental health disorders[120] like anxiety and depression. Biofeedback techniques are not only utilized in clinical settings; they are becoming tools that ordinary individuals can employ in their daily lives to maintain and enhance their health[121]. Notably, HRV biofeedback has demonstrated efficacy in reducing stress, anxiety, and depression in non-clinical populations[122], two studies examined the effectiveness of a computer-based heart rate variability biofeedback programmed in reducing anxiety and negative mood in college students. The first study showed a substantial decrease in anxiety and negative mood after 4 weeks of using the programmed. The impact of the second study was not as strong.

Emerging interactive technologies have facilitated the seamless integration of biofeedback into daily environments, thereby enhancing its accessibility, usability, comfort, and user-friendliness[120]. Judith Esi van der Zwan et al. (2015) conducted a study in which participants utilized an HRV biofeedback device for at-home slow breathing exercises, the device was StressEraser, when using it , participants utilized the 'breathe program' to assess their personal breathing frequency, aimed at maximizing HRV[123]. The findings indicated an overall beneficial impact, including stress reduction, alleviation of anxiety and depressive symptoms, as well as improvements in mental well-being and sleep quality. VR-based biofeedback is a relatively recent intervention that is increasingly being utilized in the treatment of anxiety disorders[124], demonstrating efficacy in reducing psychological stress as well[125]. In the experiment, a chest strap was used to record cardiac activity while participating in a virtual environment via an HMD. Changes in HRV scores cause discrete changes in the virtual environment. Specifically, increases in HRV cause flowers to grow in the meadows, the sun to rise on the horizon, and natural soundscapes to enhance

1.2 Motivation

Biofeedback technology significantly benefits both the mental and physical health of individuals. Nevertheless, the majority of biofeedback methods necessitate visits to physical therapy clinics, medical centers, and hospitals, where individuals rely on professional equipment and guidance from trained experts. Given the fast-paced nature of modern work and study routines, allocating time for biofeedback training requires careful planning, additional attention, and effort. This potential inconvenience may exacerbate mental stress and psychological burdens.

There is a growing demand for biofeedback solutions intended for home use, home-based biofeedback therapy devices and programs are becoming integral components of health management. Their proliferation not only allows individuals to receive high-quality biofeedback training at home but also reduces the pressure and time costs associated with visits to medical institutions. It is important to note that home-based biofeedback technologies are not restricted to specific demographics. They exhibit broad applicability, catering to individuals of varying age groups and health conditions. Whether for managing daily stress, alleviating symptoms of anxiety, or aiding in the rehabilitation process, these technologies offer personalized and effective solutions. In order to monitor one's health more flexibly so that timely adjustments and interventions can be made to maintain physical and mental health. People need convenient devices to monitor physiological indicators such as heart rate, temperature.

Motivated by the need to remove the above-mentioned limitations of location and negative effects of biofeedback training, and to ensure that when using these biofeedback technologies or devices, they do not disrupt our daily lives nor demand additional attention or effort. We conducted three topic studies.

The first topic is about respiration-posture feedback. While numerous studies have investigated the physiological and psychological benefits of actively regulating breathing[143,144,147], there is a notable dearth of research regarding the capacity to regulate respiration without necessitating active intervention. Based on the need to regulate breathing without conscious effort, in a previous study, a respiration-posture feedback system was developed, which aims at involuntary breathing control via posture intervention, a rubber air chamber, positioned beneath the participant's back, inflates and deflates to induce slight vertical movements in the participant's upper body while lying on a bed. Results demonstrate the efficacy of postural intervention on respiratory regulation, activating cardiac parasympathetic nerves and reducing tension and peripheral sympathetic activity [144]. However, the correlation between posture displacement and the effect of feedback on respiration remains uncertain. This study replaced the previous inflatable pillows with electrical lift for more precise control over the amplitude of posture changes. Research in this area could contribute to explore a new method to control breathing in the home environment.

The second topic is about heartrate feedback relaxing music. In everyday life, a substantial number of individuals often engage in listening to music as a means of relaxation or to pass the time. Realizing heartbeat interaction involves the monitoring of an individual's heart rate synchronized with the tempo of music being listened to. Despite its potential for inducing beneficial physiological and psychological effects, scientific investigation in this area remains limited. Furthermore, the versatility of this technology allows for usage across various scenarios, with the added advantage of being implementable within a home environment. A comprehensive examination of its applications and implications is warranted, as it could hold promise for enhancing well-being through personalized music therapy. The motivation was to develop a heart rate-based music feedback architecture that biologically induces psychophysiological effects.

The third topic is about a new method of human pulse measurement using consumer earphones and headphones. Unlike the method of measuring HR using PPG, this approach is a straightforward signal separation method that utilizes pressure changes resulting from heartbeats within the ear canal. HR monitoring is essential for biofeedback training and for individuals who require daily monitoring. This method is feasible for almost all of the consumer earphones and headphones, and can measure HR while listening to music. HRV can reflect the status of cardiovascular disease and autonomic nervous function, and the method can enable accurate measurement of HRV. It has the potential to democratize access to precise HR data, empowering individuals to take proactive steps in managing their health. Research shows activity trackers appear to be effective in increasing physical activity in a variety of age groups and in both clinical and non-clinical populations[147]. This innovation holds promise in significantly enhancing individual health management practices. Recognizing these necessities, the motivation was to propose a new method of human pulse measurement using consumer earphones and headphones.

1.3 Objectives

People are paying more and more attention to personal health and are beginning to look for more comfortable and effective ways to maintain and enhance health at home. Biofeedback training and technology can help people improve their health at home. Motivated by methods to implement biofeedback training and technology in home environment, the study aims to explore the effects of posture displacement, assess the impact of feedback on respiration, and develop a proprietary bio-signal interactive music feedback architecture. Additionally, a new method for measuring human pulse using consumer-grade earphones and headphones will be introduced.

1.4 Chapter Summary Structure of the Dissertation

The dissertation was structured into six chapters as follows;

Based on health promotion methods and academic evidence from the literature, chapter 1 discusses various psychological and physiological benefits of technological interventions and biofeedback. The motivation for the research and its objectives are explained.

In Chapter 2, the background of controlled breathing is initially introduced, followed by a laboratory study focusing on the effects of a new respiration-posture feedback system. Finally, the results obtained under various posture movement distances are discussed.

In Chapter 3, the background on the efficacy of relaxing music is introduced first, followed by a preliminary study examining the psychophysiological effects of heart rate feedback relaxing music. Subsequently, the discussion focuses on the comparative results of psychophysiological effects between two conditions.

In Chapter 4. First, the products and technologies of wearable device monitoring heart rate are introduced, then a new method of human pulse measurement using consumer earphones and headphones is introduced, then its feasibility evaluation is studied, and finally the advantages, applications and future of this method are discussed.

Chapter 5 initiates with a summary of the research conducted across the three studies, followed by an exploration of the study's contributions in terms of theory and potential applications.

Chapter 6 describes the conclusions and possible practical functions of the system and methods.

CHAPTER 2

STUDY ON RESPIRATION-POSTURE FEEDBACK

In this study, we developed a new kind of respiration-posture feedback system where participants lied down and rested on the bed and their back was moved up and down by a servomotor-driven lifting device in accordance with their breathing. Unlike the air chamber used in the previous studies[143], the current system changed the posture by ascending and descending a part of bed using a servo motor control. Therefore, the system can more accurately control intervention variables accurately rather than the previous system with the air chamber.

2.1 Controlled breathing

Breathing is one of the most important indicators of human vital signs. Recent theoretical developments have revealed that breathing control can reduce stress and boost the immune system[126,127]. One of the most popular ideas in biofeedback literature is the idea that breathing control benefits human both physically and psychologically[128]. Yoga, martial arts, marathons, psychotherapy, meditation utilize breathing control as a training method to promote concentration and improve vitality[129-131]. Breathing control can help reduce symptoms associated with anxiety, insomnia, post-traumatic stress disorder, depression, and attention deficit disorder[132,133].

Slow breathing exercise has been reported to influence autonomic activity such as HR and blood pressure, alleviating sympathetic nervous system activity and promoting parasympathetic nervous system activity[134-136]. Slow breathing usually results in an increase in alpha power in the brain and leaving us physically and mentally relaxed[137,138]. Breathing training to take a deep breath is widely used in the training of athletes and the clinical treatment of mental illness, such as post-traumatic stress disorder and movement disorders[137].

While the voluntary breathing control requires continuous effort and concentration, leading to difficulty to continue, an external control of body posture can induce involuntary changes in respiration. Leaning back makes inhalation easier and expiration more difficult, and conversely, hunching forward makes inhalation more difficult and expiration easier. In other words, changing the posture of the human body can change respiration resistance.

The previous studies conducted were instigated by a common sense: the curvature of the human back has an impact on respiratory patterns[143,144]. A posture control system was developed with an air chamber placed beneath the participant’s backside intervening the posture as being synchronously with respiration. A feasibility study involved a short, five-minute intervention with seven male participants, revealing a significant increase in respiration interval and amplitude, as well as heightened high-frequency components. In the subsequent experimental study with ten participants, three conditions were tested: synchronous, Asynchronous, and Constant. Results showed that under synchronous, respiration interval and amplitude increased significantly compared to other conditions[143]. While psychological scores did not show significant changes, a notable reduction in 'tension' was observed in the synchronous condition. HRV analysis indicated a decrease in the high-frequency component during the synchronous intervention period, and EDA decreased during intervention and increased during recovery. High-frequency indices are commonly and frequently utilized in human evaluation studies, such as those in psychophysiology, as they serve as indicators of autonomic nervous system activity[145]. These findings suggest the efficacy of respiration regulation through posture intervention. The study suggests potential applications in healthcare equipment for clinical treatments addressing involuntary deep breathing in patients with breathing-related disorders.

In these studies, postures were changed by inflating and deflating the air chamber under the participant’s back[143,144]. However, the air chamber was not necessarily suitable for accurate and quantitative control of the body posture because the displacement depends on individual body size and time-consuming air injection. In this study, a new type of respiration-posture feedback system was developed, unlike the air chamber used in previous studies, a servomotor-driven lifting device placed under a bed to make a participant’s upper body move vertically while lying on the bed. Therefore, the system can more accurately control intervention variables compared to the previous system with the air chamber.

Precise posture control may allow us to manipulate respiration because changes in body posture can have a significant impact on lung function, leading to modifications in the mechanics of respiration. Mechanoreceptors are widely distributed throughout the respiratory system, specifically in the airways, trachea, lungs, and pulmonary vessels. These specialized cells are responsible for providing crucial sensory feedback to the nervous system. Within the lungs, stretch receptors are classified into two types based on their response characteristics: slow-adapting and rapidly adapting[148]. Especially, slow-adapting receptors are activated during lung inflation and are integral to the Hering-Breuer reflex, which terminates inspiration and prolongs expiration[148,149]. The lung mechanoreceptors are highly sensitive to variations in lung volume and pressure, and they play a crucial role in detecting alterations in the respiratory pattern. In terms of mechanical view, if the physical intervention activates mechanoreceptor directly, the size of the posture displacement would be associated with the magnitude of physiological effect on respiration. To investigate the impact of posture displacement and the effect of feedback on respiration. The experiment consisted of four conditions with varying maximum lifting heights: 0.5 cm, 1 cm, 3 cm, and 6 cm. We thus hypothesized that physiological indices of respiration change proportionally to the amount of lifting height in our system. In order to test this hypothesis, we conducted experiments that participants performed with the posture displacement having different heights.

2.2 Respiration-posture feedback system

2.2.1 Architecture

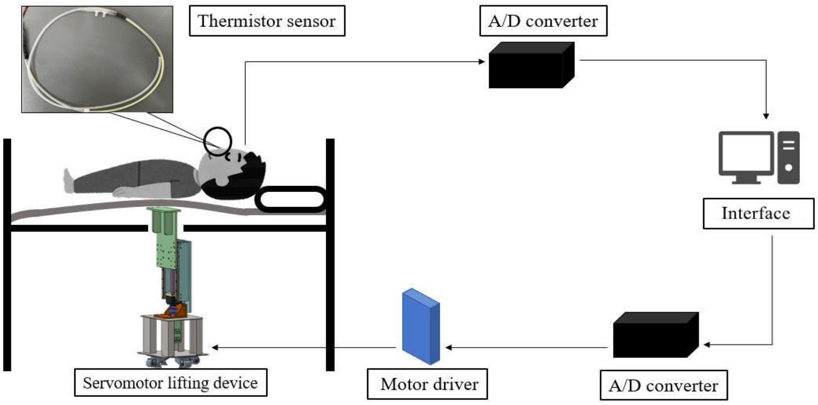


Figure2: Schematic diagram of the servomotor-based respiratory posture feedback system.

Figure3:Experimental setup used in this study. Participant lied down on a single bed equipped with the lifting device.

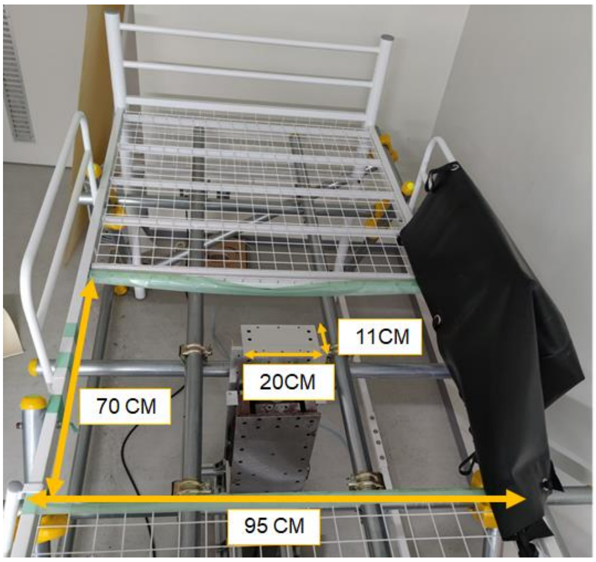


Figure4: The lifting device in the middle of aperture in the bed. The lifting table, 20cm by 11cm, changed the position of participant’s back up and down.

We developed a respiration-posture feedback system where back of participants lying down was moved up and down by a servomotor-driven lifting device in accordance with their breathing (Figure 2 and 3). This system consists of: (1) the respiration sensor(Using an Negative Temperature Coefficient-based temperature sensor to measure participants’ respiratory rate with high sensitivity and fast response, characteristic curve is shown in Figure 5) unit comprised of a thermistor (Murata Manufacturing Co., Ltd., Japan) in nostril cannula placed on the participant's philtrum near the nose, to detect respiration as a change in the temperature, (2) analog-to-digital (A/D) converters (NI USB-6008 DAQ and NI USB-6212 DAQ, National Instruments Co., USA) which monitors the participant’s respiration with 12-bit resolution and 1kHz sampling rate, and, (3) the posture regulation unit consists of a lifting mechanism with a servo motor (NXD75-S, Oriental Motor, Japan) located beneath the bed board, allowing for vertical movement. In this system, the move up and down of the lift make the participant's upper body move vertically while lying on the bed (Figure 4). The lift's movement was regulated by feedback regulation synchronized with the participant's actual respiration. This feedback regulation was achieved using a posture feedback controller interface developed with a visual programming language (LabVIEW, National Instruments Co., USA), which controlled the servomotor.

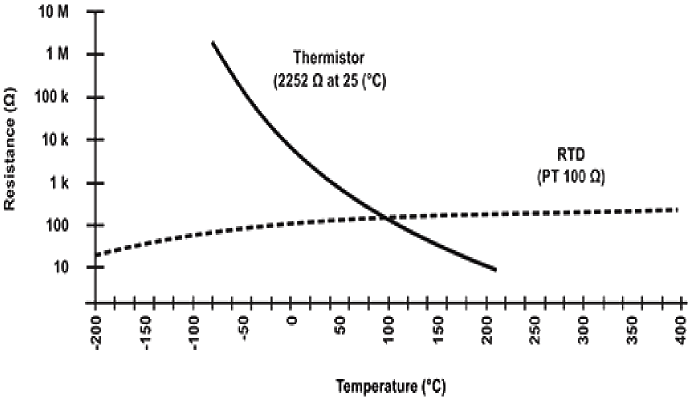


Figure 5: Negative Temperature Coefficient-based characteristic curve[150].

2.2.2 Algorithm

Figure 6 shows the example timing chart of the feedback system. The respiration signal of the participant was differentiated to cut off the baseline changes and variations of the original signal. A threshold value for the inhalation detection of each participant was set during the initialization period of 4 min before each experimental trial. According to the algorithm, an inhalation is detected once the differential wave reaches each threshold value, then the lift moved up from its initial position to h/2 cm above the bed surface for 4 seconds and moved down to the initial position for 4 seconds. Range of the lift movement (h cm) determined the four experimental conditions in the study.

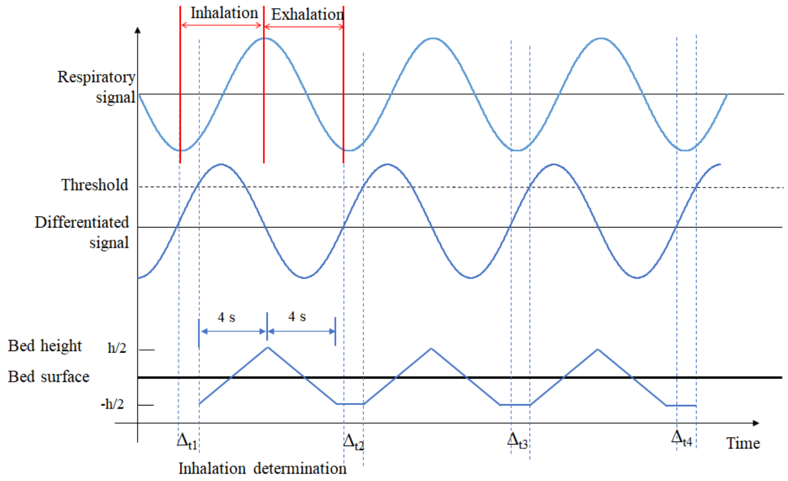


Figure 6: Relationship between Respiration and Movement. In the h cm condition, the lift initially positioned itself at h/2 cm below the surface of the bed. Subsequently, upon detecting an inhalation indicated by a differentiated signal transitioning from negative to positive, the lift ascended to h/2 cm above the surface within a 4-second interval, before descending back to its initial position over the subsequent 4 seconds.

With the respective time delay (Δt_i) and 4 seconds period of ascending, the inhalation can be lengthened as the changed body posture makes the exhalation difficult. Similarly, 4 seconds descending can lead to lengthened exhalation. The posture intervention might affect the pressure in the lungs by stimulating the mechanoreceptors of the lungs. This could induce vagus nerve activation and intervene with the participant's breathing by making it deeper and longer[143].

2.3 Participants

The study consisted of 21 healthy male university students aged 22 to 24 years old. All participants did not have any particular symptom or respiratory disorder. Participants included in the study were instructed to sleep well a few days before the experiment and avoid consuming alcohol the day before the experiment. They were asked not to drink and eat anything but water, nor to exercise vigorously one hour before the experiment.

The study was conducted in accordance with ethical principles and informed consent was obtained from all participants. The research was approved by the ethics committee of Nagaoka University of Technology (Sei R3-2).

2.4 Experimental protocol and conditions

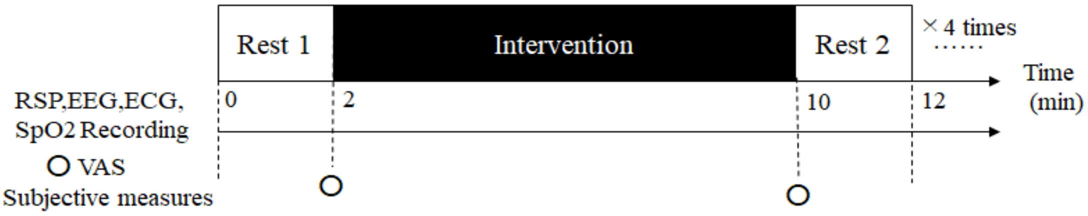


Figure 7: The experimental protocol with four conditions performed in a counter balanced order (within-subject design).

We conducted a within-subject design laboratory experiment with four conditions: 0.5 cm, 1 cm, 3 cm, and 6 cm in vertical amplitude of the lift. According to the preliminary tests, the participants were uncomfortable when the vertical amplitude is over 6cm and they did not feel any change in movement if below 0.5cm. Therefore, the conditions were set from 0.5 cm to 6 cm.

Participants performed the four trials corresponding to the conditions sequentially without any intervals in a counter-balanced order (Figure 7). Each trial lasted for 12 minutes, including an initial 2-minute rest period (R1), an 8-minute intervention period, and a 2-minute recovery period (R2). The participants were instructed to lie calm and supine on the bed during the experiment. To ensure proper alignment, their position was adjusted so that the navel was directly above the lift. The posture intervention by the respiration-posture feedback system was made during the intervention period. In the intervention period, the room was darkened and the participants were asked to close their eyes. The experiment was conducted in an air-controlled laboratory room, with an average ambient temperature of 25°C.

2.5 Measurements

2.5.1 Physiological measurements

Respiration was measured at 1 kHz at a sampling rate by a bio-signal amplifier system (MP150, BIOPAC Systems, Inc., USA) with the thermistor also used in the feedback system. Respiration intervals and respiration amplitudes were obtained by peak detection of the respiration signal. An ECG was recorded by a bio-signal amplifier (Polymate Pro MP6000, Miyuki Giken, Japan). Electrodes were placed under right clavicle and on lower left abdomen, so-called “Lead II” induction. The HR and the high-frequency component (HF; range: 0.15 – 0.40

Hz) and the low-frequency component (LF; range: 0.03 – 0.15 Hz) of HRV were obtained using AcqKnowledge software version 4.1 (BIOPAC Systems, inc., U. S). Electroencephalogram (EEG) at C3, C4, O1, and O2 with references (A1 and A2) by the 10-20 international system was recorded by the same bio-signal amplifier as the ECG with 16-bit resolution and at 500Hz sampling rate, using a 50-Hz notch filter (a HF 60 Hz filter and a LF 0.53 Hz filter). As for frequency domain analysis, alpha (8-12 Hz) and beta (13-30 Hz) power of EEGs were calculated for every one-minute time window using a proprietary software for the bio-amplifier (AP Viewer 4.12A, NoruPro Light Systems, Inc., Japan). Additionally, an oxygen saturation (SpO_2) sensor (g. tec medical engineering GmbH, Australia) was fixed to the participant's index finger in the non-dominant hand. The SpO_2 was measured to monitor participants' oxygen concentration for safety reason. Each signal was recorded continuously throughout the experiment.

2.5.2 Psychological measurements

Subjective evaluations of the participants were completed by a Visual Analog Scale (VAS), with a calibrated line of two endpoints (minimum and maximum) comprising 5 items; "comfort", "fatigue", "ease of breathing", "difficulty in breathing", and "drowsiness". The participants rated their impressions for each of the five items on the respective point before and after the intervention period (Figure 7).

2.5.3 Data analysis and statistics

All participants had an above 98% SpO_2 value during the intervention period except one participant whose SpO_2 value dropped below 80% for more than 20 seconds, leading to the interruption of the experiment. The participant's involvement in the experiment was terminated 23 minutes after its initiation due to low SpO_2 levels. The figure 8 shows the participant's respiration data prior to the experiment's interruption, A1 and A2 denote distinct channels designated for signal acquisition. Specifically, A1 corresponds to channel 1, while A2 corresponds to channel 2. Data collected during the experiment were as normal as other participants. Subsequent investigation revealed that the low SpO_2 levels were attributable to a loose connection between the SpO_2 sensor and the participant's finger. Therefore, we analyzed data from 20 participants.

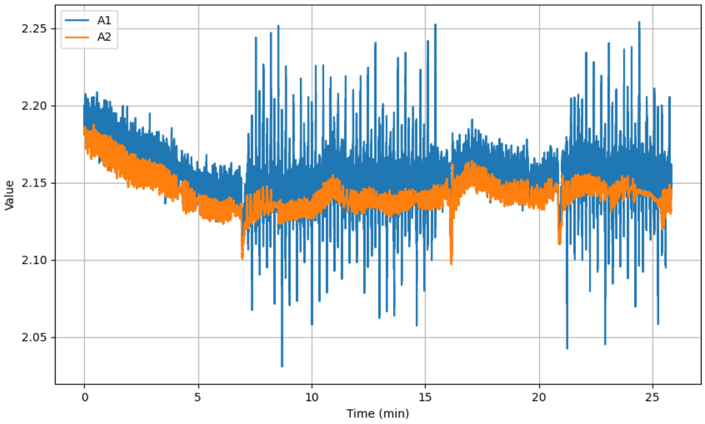


Figure 8: Respiration information for the participant whose experiment was interrupted.

The raw values of the bio-signal data were standardized (z-score) throughout the experiment of each condition considering each participant and condition, owing to significant individual variations. The values were baseline-corrected with respect to the mean value of the first rest period. A paired t-test with Bonferroni corrections was made for comparison among the four conditions. The statistical significance level was set to $p < 0.05$.

Note that the mean alpha (α) power and mean beta (β) power values of respective electrodes (O1, O2, C3 and C4) were considered to perform the statistical analysis for the EEG data. As an example, the averaged α power value of C3 and C4 electrodes were obtained and denoted by C (α). Similarly, C(β), O(α), and O(β) were obtained.

Differences of VAS scores from pre-intervention to post-intervention were calculated. A paired *t*-test was used for comparisons within and between conditions with a significance level of $p < 0.05$.

2.6 Results

2.6.1 Respiration parameters

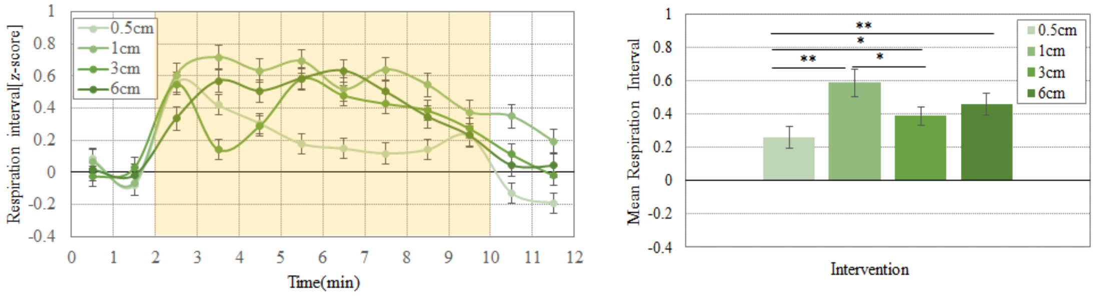


Figure 9 (a) Figure 9 (b)

Figure 9 : (a): Profile of the change in the respiration interval in 0.5cm, 1cm, 3cm, and 6cm conditions. The period in a yellow background represents intervention. (b): Mean respiratory interval value (mean ± SE).

Figure 9 (a) illustrates the changes in respiration interval under different conditions. Figure 9(b) shows the mean respiratory interval value during the intervention. Compared with the 0.5cm condition, the respiration interval in the 1cm, 3 cm, and 6 cm conditions were significantly higher (1cm: t_{19}[19] =5.11, p < 0.001; 3cm: t_{19} =2.73, p=0.013; 6cm: t_{19} =4.22, p< 0.001). Moreover, the respiration interval in the 1cm condition was significantly higher than that in the 0.5cm condition and 3cm condition (0.5cm: t_{19} =5.11, p < 0.001;3cm: t_{19} =2.45, p =0.020).

2.6.2 Heart Rate and Heart Rate Variability

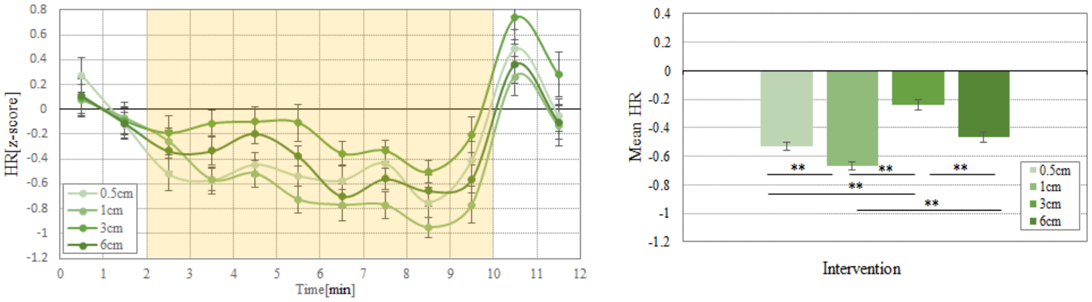


Figure 10 (a) Figure 10(b)

Figure10: Heart rate (a): Profile of the change in the heart rate in 0.5cm, 1cm, 3cm, and 6cm conditions. (b): Mean HR value (mean ± SE).

Figure 10(a) displays the changes in HR observed during the intervention period. Figure 10(b) presents the average change in HR during the intervention period. Notably, the HR recorded during the intervention with a 1cm condition was significantly lower than that of the other conditions (0.5cm: t_{19} =4.83, $p < 0.001$; 3cm: t_{19} =11.36, $p < 0.001$; 6cm: t_{19} =5.22, $p < 0.001$), while the HR observed during the 3cm condition was significantly higher than the other conditions (0.5cm: t_{19} =7.10, $p < 0.001$; 1cm: t_{19} =11.36, $p < 0.001$; 6cm: t_{19} =6.06, p=0.008).

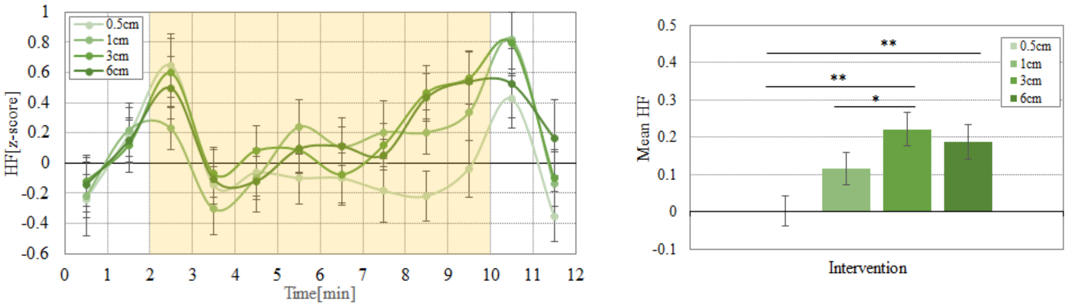


Figure 11 (a)

Figure 11 (b)

Figure 11: HF component of HRV (a): Profile of the change in the HF component in 0.5 cm, 1 cm, 3 cm, and 6 cm conditions. (b): Mean HF component value (mean ± SE).

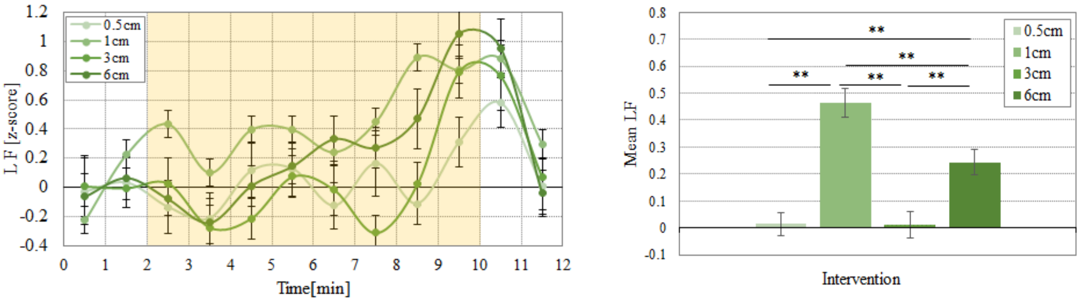


Figure 12 (a)

Figure 12 (b)

Figure 12: LF component of HRV (a): Profile of the change in the LF component in 0.5cm, 1cm, 3cm, and 6cm conditions. (b): Mean LF component value (mean ± SE).

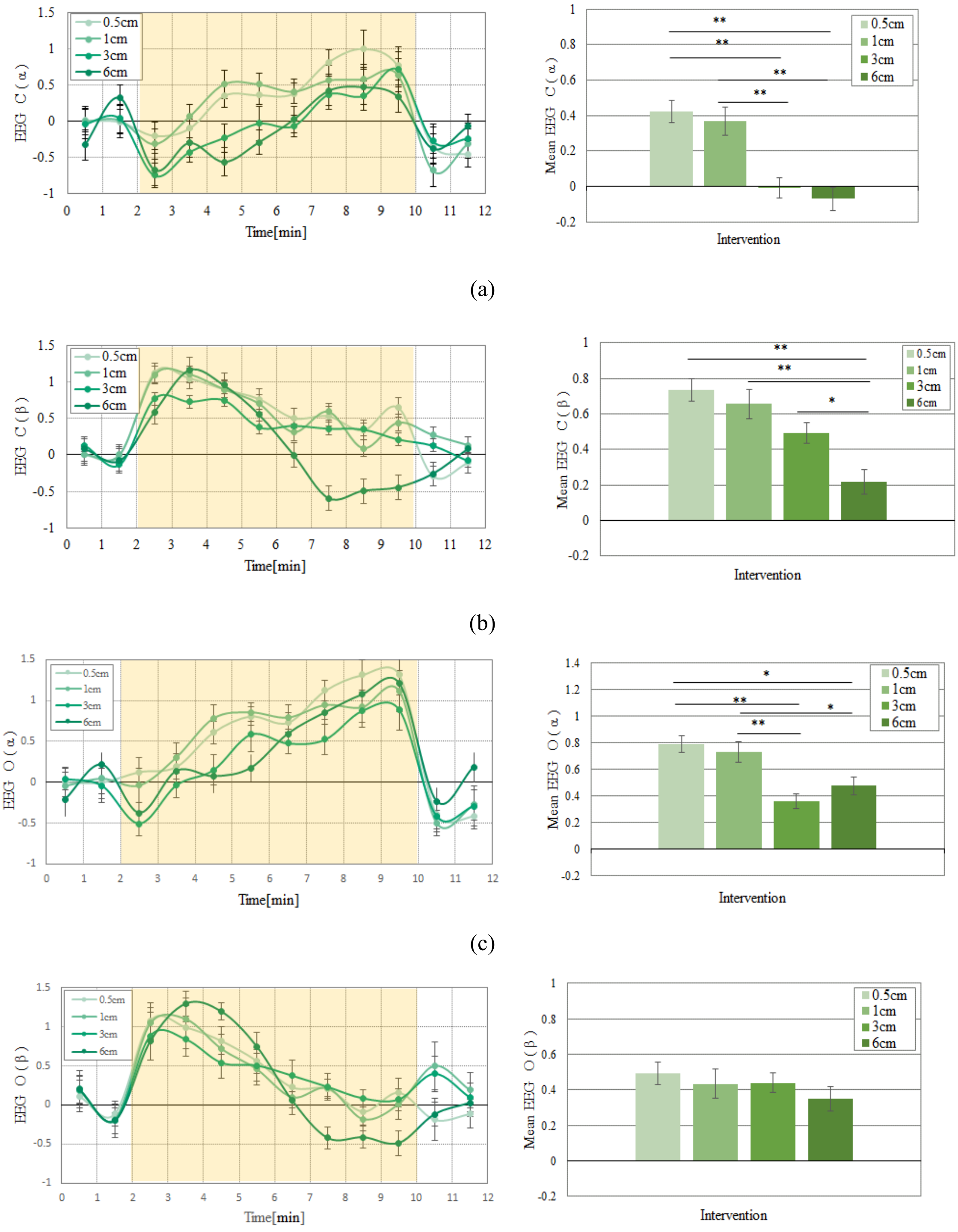
The HF and LF components of HRV for the four conditions are presented in Figure 10 (a) and Figure 11(a), respectively. Based on the mean HF component values during the intervention period, as depicted in Figure 11 (b), the increase of HF in the 0.5cm condition was significantly lower compared to the 3 and 6 conditions (3cm: t_{19} =3.96, $p < 0.001$; 6cm: t_{19} =2.89, p=0.009). However, the increase of HF in the 3cm condition was significantly higher compared to the 1cm condition (1cm: t_{19} =2.18, $p < 0.05$).

Based on the mean LF component values during the intervention period, as presented in Figure 12(b), the 1cm condition showed a significantly higher increase in LF compared to the other three conditions (0.5cm: t_{19}=8.05, $p < 0.001$; 3cm: t_{19}=9.67, $p < 0.001$; 6cm: t_{19} =4.48, $p < 0.001$). In contrast, the increase in LF with the 0.5cm and 3cm conditions was significantly lower than that with the 6cm condition (0.5cm: t_{19} =4.10, $p < 0.001$; 3cm: t_{19} =4.95, $p < 0.001$).

2.6.3 Electroencephalogram

Figure 13 illustrates alterations in the alpha and beta wave components of EEG at electrode position O and C. In some past studies on alpha and beta waves, alpha and beta EEG recorded from the occipital (O1-A2 and O2-A1) and central (C3-A2 and C4-A1) channels[151,152]. In this study, the mean alpha (α) power and mean beta (β) power values of respective electrodes (O1, O2, C3 and C4) were considered to perform the statistical analysis for the EEG data. As the focus of this analysis does not involve comparing O1 and O2, they are considered together as a single entity, as are C3 and C4. Concerning site C, the increase in alpha wave components under the 0.5cm condition was significantly higher than in the 3cm and 6cm conditions (3cm: t_{19} = 6.16, $p < 0.001$; 6cm: t_{19} = 7.56, $p < 0.001$). Similarly, in the 1cm condition, the increase in alpha wave components exceeded that of the 3cm and 6cm conditions (3cm: t_{19} = 5.48, $p < 0.001$; 6cm: t_{19} = 8.67, $p < 0.001$). Additionally, the increase in beta wave components in the 6cm condition was significantly smaller than in the other three conditions (0.5cm: t_{19} = 7.43, $p < 0.001$; 1cm: t_{19} = 6.53, $p < 0.001$; 3cm: t_{19} = 3.61, $p < 0.05$).

As for site O, the increase in alpha wave components under the 0.5cm condition was significantly higher than in the 3cm and 6cm conditions (3cm: t_{19} = 8.22, $p < 0.001$; 6cm: t_{19} = 5.42, $p < 0.05$). Similarly, in the 1cm condition, the increase in alpha wave components surpassed that of the 3cm and 6cm conditions (3cm: t_{19} = 6.13, $p < 0.001$; 6cm: t_{19} = 4.65, $p < 0.05$). However, no notable disparities were observed in the augmentation of beta wave components among the various conditions.



(a)

(b)

(c)

(d)

Figure 13: Profile of the change in the alpha and beta wave components of C (a, b), O (c, d) in 0.5cm, 1cm, 3cm and 6cm conditions.

2.6.4 Subjective measures

Table 3: Results (mean and SD) of subjective measures (VAS)

Item	Condition	Before to after the intervention	
		Mean	(SD)
Comfort	0.5cm	-1.7	(-1.18)
	1cm	-0.95	(-5.76)
	3cm	4	(2.16)
	6cm	7.7	(-2.27)
Fatigue	0.5cm	-5.95	(1.70)
	1cm	-2.9	(3.25)
	3cm	-8.65	(-2.23)
	6cm	-9.85	(0.40) **
Ease of breathing	0.5cm	-1.3	(3.70)
	1cm	8.15	(-3.27)
	3cm	1.95	(-1.91)
	6cm	5	(0.01)
Difficulty in breathing	0.5cm	-1.15	(3.00)
	1cm	-7.95	(-4.54)
	3cm	-5.25	(-3.53)
	6cm	-3.1	(-3.51)
Drowsiness	0.5cm	-8.35	(-0.99)
	1cm	-6.65	(-1.53)
	3cm	-5.6	(1.43)
	6cm	5.55	(0.81)

** $p < 0.01$ by comparison within condition

Table 3 shows the differences of the subjective VAS scores from the post- to pre-intervention. Out of all the items examined, only "Fatigue" showed a significant increase in the 6 cm condition (Fatigue in 6 cm: $t_{19} = 3.02, p= 0.006$). No other items showed significant differences or trends within or between the conditions.

2.7 Discussion

This study aimed to regulate participants' respiration while in a lying position by manipulating their posture. We achieved this through a respiration-posture feedback system utilizing a servomotor-driven lifting device, adjusting the participant's back in sync with their respiration, it is hypothesized that physiological indices of respiration change proportionally to the amount of lifting height in the system. Physiological measures, including respiration parameters, HR, HF, LF components of HRV, and EEG were examined.1cm was significantly higher than that in the 0.5cm and 3cm condition in the RI. Additionally, 1cm condition was significantly lower than the other conditions in HR There was a significant higher in the LF component in the 1 cm condition compared to the other conditions. In the 3 cm condition, the HF component was significantly higher compared to the 1cm condition. Furthermore, the alpha wave components showed a significantly higher in the 1 cm condition than 3cm and 6cm, for both site C and O. In terms of subjective participant impressions, "Fatigue" was significantly higher in the 6 cm condition. Contrary to our hypothesis, the effects of intervention did not increase proportionally with the motion range of the lifting device. Notably, most physiological data from the 1 cm condition differed significantly from the other conditions. These findings imply that the respiration-posture feedback system was more pronounced under the 1 cm intervention condition.

The significant increase in RI indicates the effectiveness of the respiration-posture feedback system in prolonging participants' breathing. Additionally, the results reveal a decrease in HR, reflecting reduced sympathetic nervous system activity. The HF component of the heart rate variability has been frequently taken as an index of cardiac parasympathetic nervous system activation. The 1cm condition shows increased activity in both HF and LF. However, since it is the respiration that we intervene, both HF and LF components of HRV can change in response to alterations in respiration patterns. This phenomenon is known as respiratory sinus arrhythmia[153]. So, the increased HF (nor LF) cannot be directly interpreted as the activation of parasympathetic system.

Numerous studies have consistently demonstrated that practicing slow and deep breathing leads to an increase in the HRV index, indicating heightened vagal tone, and a reduction in stress markers such as HR, blood pressure, and salivary cortisol[154]. Our study aligns with these findings, as we observed a decrease in HR along with an increase in both the HF and LF. The vagus nerve, the tenth cranial nerve, plays a pivotal role in the parasympathetic nervous system[155]. HRV is particularly valuable as it serves as an index of cardiac vagal tone, reflecting the influence of the parasympathetic nervous system on cardiac regulation[156,157]. Activating the vagus nerve has been shown to reduce anxiety and enhance parasympathetic nervous system activity[156].

Additionally, previous research has demonstrated the impact of physical interventions on the respiratory. Francesco Crivelli (2016) developed a 6-degree-of-freedom tendon-based robotic bed to systematically evaluate vestibular stimuli. The 5-minute intervention affected participants' breathing rates, with subjective questionnaires showing that movement along the z-axis seemed most likely to promote relaxation[158]. Similarly, in our system, participants' breathing rate also changed (lengthened and deepened). However, our subjective questionnaire did not show relaxation, which may be due to different intervention time and intervention conditions.

The EEG data indicated a notable augmentation of alpha wave components in the 0.5cm and 1cm conditions. Past research has proven that alpha waves can reduce tension, stress, and anxiety, and boost immunity[159,160]. Study also finds slow breathing technique promotes increased alpha power[161]. It may be that deep breathing caused by the respiration-posture feedback system enhances alpha waves.

Previous study demonstrated that the participant’s respiration was significantly lengthened by regulating the inflation and deflation of the rubber air chamber[143,144], which is consistent with this study. Both studies utilized body posture as the intervention condition, which is a shared similarity between them. This study differed from the previous one in several ways, including the use of a lift instead of a chamber to change body posture, experimental conditions and algorithms, and the measurement of additional physiological parameters.

To our knowledge, only a limited number of studies have explored body posture interventions aimed at modifying respiration patterns. Body posture can also affect pulmonary function[163]. In a study by M. Romei (2010), it was found that posture and gender exert a significant influence on breathing patterns and chest wall kinematics. Consistent with these findings, the present study demonstrates that body posture influences respiration patterns[162]. We observed the physiological and psychological effects of interventions on body posture in the supine position.

In most instances, our respiration operates involuntarily. Yet, during activities such as yoga, meditation, and similar practices, conscious adjustment of breathing rate and depth may be required. By contrast, our system focuses on controlling involuntary respiratory by a respiratory-posture feedback regulation. Once the system is activated, the user can achieve breath control without requiring care or attention. Almost one billion individuals globally suffer from OSA as defined by 5 or more events per hour, this includes 425 million adults aged 30-69 experiencing moderate to severe OSA (15 or more events per hour)[164]. In contrast to forced ventilation methods for treating OSA, our system presents the convenience of not necessitating catheter insertion or the use of a breathing mask. This attribute underscores the innovativeness of our system.

This study is not without limitations, and it is important to acknowledge this when interpreting our research findings. Initially, the findings were confined to male participants. As all participants were male and predominantly around the age of 22, the generalizability of the research results to other age groups or the entire population, including females, may be limited. Study finds gender has significant impact on respiratory system structure and function[165]. In the general population, women have a significantly higher prevalence of dyspnea than men [166]. Future experiments should incorporate female participants to enhance the generalizability of the findings. In addition, physiological measurement cables or electrode pads may cause discomfort or restriction to participants during the experiment. To mitigate this potential constraint, it is advisable for future studies to investigate the feasibility of employing wireless measurement techniques, thereby establishing more optimal experimental conditions[167-169]. For instance, considering the substitution of a bioimpedance (BioZ) sensor for the nasal thermistor to monitor respiration rate[170]. For respiration detection, utilizing image processing is considered the easiest way. This method involves analyzing video footage or images captured of the participant 's chest or abdomen region to track movement patterns indicative of breathing. Specifically, image processing algorithms are employed to identify and track the expansion and contraction of the chest or abdomen over time, allowing for the detection of respiratory movements. This non-invasive technique offers a convenient and efficient means of monitoring respiration without the need for direct contact with the participant's body.

2.8 Chapter Summary

This chapter provides a comprehensive overview of the respiration-posture feedback system. Upon comparing the conditions of 1 cm with both 0.5 cm and 3 cm, a noticeable increase in RI was observed. Specifically, in the 1 cm condition, there was a significantly lower HR compared to the other conditions. Additionally, there was higher in the LF in the 1 cm condition, setting it apart from the other conditions. Furthermore, the increase in HF in the 3 cm condition was higher compared to the 1 cm condition. Moreover, alpha wave components exhibited a surge in the 1 cm condition, distinguishing it from both the 3 cm and 6 cm conditions, for both conditions denoted as C and O. The respiration-posture feedback system was developed to the regulation of breathing, resulting in successfully lengthened and deepened respiration. The system demonstrated greater effectiveness under the 1 cm intervention condition.

CHAPTER 3

STUDY ON HEARTRATE FEEDBACK RELAXING MUSIC

Chapter 3 initiates a preliminary investigation into the psychophysiological effects generated by the integration of HR feedback and relaxing music. This chapter primarily introduces our developed architecture for HR music feedback, where the rhythm of the music tracks dynamically adjusts based on the user's heartbeat. It is assessed in real-time and subjected to initial experiments to explore its psychophysiological effects within a laboratory setting.

3.1 Relaxing music

The positive efficacy of relaxing music has been well documented regardless of the type of study setting and target participants. Most commonly, it has been demonstrated that relaxing or sedative music reduces anxiety and tension feelings and decreases HR, blood pressure, and respiration rate (e.g.[171-173]). One study reported the overall benefit of music for people who have been emotionally vulnerable during the COVID-19 pandemic[174], and such a positive efficacy of music can be seen regardless of age, gender, and ethnicity; even found for premature infants[175]. Additionally, various benefits of music have been reported in the context of clinical studies and complementary medicine, such as acute, procedural, and chronic pain relief[176], improving quality of life for terminal cancer patients[177], alleviating blood pressure and respiration rate of abdominal surgery patients[178], and improving symptoms due to pulmonary disease[179] and dementia[180].

There is an existential story as a mother’s heartbeat makes her newborn baby relax. Although to the best of our knowledge, there has not been a line of studies that consolidated this story, one study reported that the mother’s heartbeat contributes to the development of the brain of newborns[181]. In addition to this study, the possible interactions between music and heartbeat have been demonstrated earlier. One study designed a special music track in which the tempo of the music was modified in accordance with the participant’s heartbeat demonstrating the increase in HRV, suggesting its sedative effect[182]. Another study observed the entrainment of HR by sedative music in which the tempo gradually decreased[183]. As for the case of interaction of the heartbeat with other than music, one study reported that the heartbeat interactive VR gave an impression to the participants as such the interactive VR contents seemed to be comfortable and natural[184].

Despite the aforementioned possible psycho-physiological effect of the bio-signal interactive architecture, it has not been experimentally investigated in a laboratory setting. Few studies have implemented such an architecture in the first place. (the study [182]is a leading-edge laboratory study. Yet, the architecture of the system and the experimental condition are not described in detail). To implement the music heartbeat interactive architecture, the tempo of the music has to be changed without altering the pitch (or key) of the music; it is technically challenging. Moreover, continuously changing the tempo of music in a real-time manner with a precise measurement of the HR and feedback algorithm should be implemented. The primary objective of this study is to develop our proprietary heart rate music feedback architecture. The secondary objective is to explore the psychophysiological effects, if any, of such a bio-signal interactive system in a laboratory setting.

3.2 Participants

Eleven male university students with a mean (±SD) age of 20.9 (±1.08) years voluntarily participated in this study. All participants had normal hearing and did not have any impairment of other sensations. The experimental design was approved by the ethics committee of the Nagaoka University of Technology.

3.3 Methods

3.3.1 Architecture

Figure 14 shows the conceptual diagram of our developed heartrate music feedback system, in which the tempo of music is sequentially changed in accordance with the instant HR (algorithm for the change is described later) in a real-time manner.

The system consists of three modules as follows:

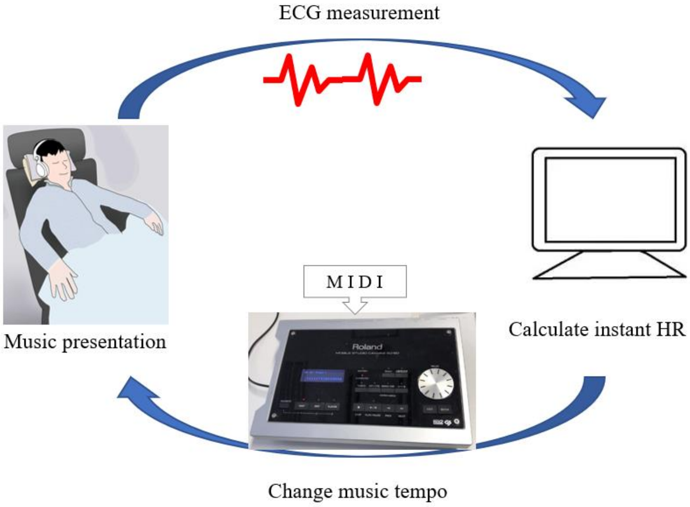
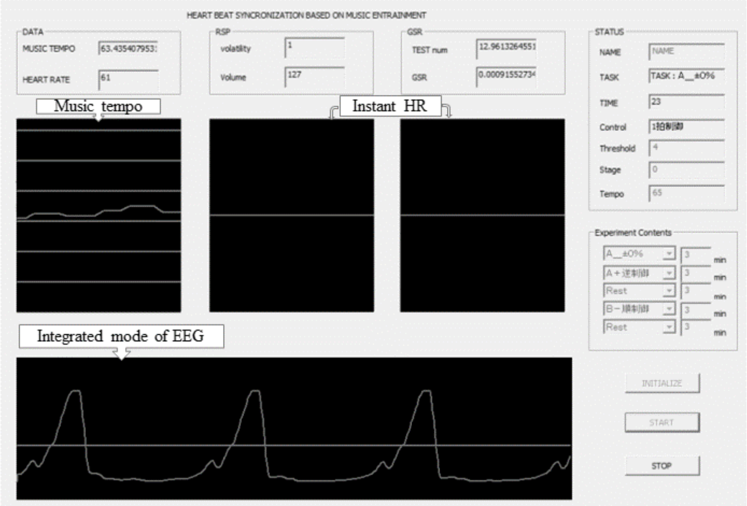


Figure 14 : Conceptual diagram of the developed heartrate music feedback system

1) Sensing Module, where ECG of users is obtained by a bio-signal amplifier device (MP150, BIOPAC Systems, Inc. USA) with 16-bit resolution and at 500Hz sampling rate. The obtained analogue data is conveyed to Control Module via application programming interface (Hardware API ver1.1, BIOPAC Systems, Inc.).

2) Control Module, where R-R interval (RRI) is sequentially determined from the obtained ECG signal. Using the RRI, tempo of music is changed at every moment when RRI is updated by means of the formula (1),

$$T_i = T_c * HR_i / HR_{av} \ \ (i = 0, 1, 2, \ldots) \quad \cdots (1)$$



MUSIC TEMPO 63.435407953
HEART RATE 61
volatility 1
Volume 127
TEST num 12.9613264551
GSR 0.0009155273
NAME NAME
TASK TASK : A__±0%
TIME 23
Control 1拍制御
Threshold 4
Stage 0
Tempo 65
A__±0% 3 min
A＋逆制御 3 min
Rest 3 min
B－順制御 3 min
Rest 3 min

Figure 15: Interface of the heartrate music feedback system

where HR_i is the instant HR calculated by i^{th} RRI from the beginning of the music play, HR_{av} is an averaged heart rate of a user which is obtained beforehand (see 2.2.2 in detail), T_c is the original tempo of music tracks, and T_i is our defined music tempo. By its formula, eventually, the music tempo changes from moment to moment in accordance with users' heartbeat; if the heart beats get faster, so does the tempo, and vice versa. This module was implemented with our developed interface (Figure 15) using the Musical Instrument Digital Interface (MIDI) programming tool kit provided by[185]. The MIDI is a standardized communication protocol that was proposed and adopted by the electronic music industry. Its primary purpose is to facilitate the interconnection and communication between electronic musical instruments, particularly synthesizers, from different manufacturers. MIDI enables the creation of cross-platform performance environments by providing a common language for musical devices. In this study, MIDI supports real-time communication, allowing for immediate adjustment of musical parameters in response to changes in HR.

3) Intervention Module, where the audio source of music tracks generated by MIDI sound module (SD-50, Roland Corporation, Japan) is presented to users with wireless headphones (Bluedio T2S Turbine 2, Guangzhou Liwei Electronics co. ltd., China).

With these three modules, the system monitors ECG and updates the tempo of music in a real-time manner. The sampling of ECG is conducted at the rate of 500Hz, meanwhile, the mean refresh rate of the system (calculating and updating the music tempo) is around 100Hz due to the computation time for the Control Module.

3.3.2 Experiment Procedure

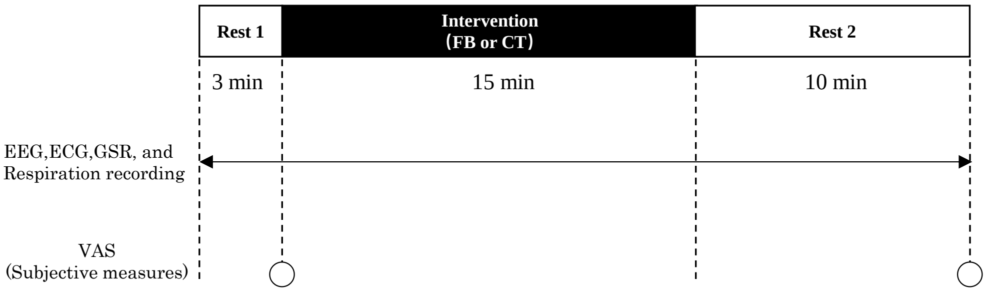


Figure 16:Experiment protocol

We conducted a preliminary experiment to explore the psychophysiological effect of the HR music feedback system. Using a within-participant design with two conditions: Feedback (FB) where the tempo of the music was continuously changed in accordance with heart rates and Constant (CT) where the music tempo was not changed at all (control condition).

Figure 16 shows the protocol of the experiment. It consists of a 3 min initialization period (namely, “Rest 1”), a 15 min intervention period (“Intervention”), and a 10 min rest period (“Rest 2”). Participants were instructed to listen to the music in the intervention period under either FB or CT conditions. As abovementioned, in FB condition, the music tempo was changed in accordance with the participants’ HR. Note that the averaged HR for each participant (HR_{av} of the formula [1]) was determined by the ECG data which was obtained in advance on the other day of the experiments. In CT, the music was played at the original tempo of the music tracks.

The music tracks used for the experiment were “Gymnopédies” composed by Erik Satie (original tempo: 64 bpm; original duration: about 3 mins and 42 seconds) and “Prelude in D flat Major, Op.28 No.15” or “Raindrop” (original tempo: 68 bpm; original duration: 5 mins and 22 seconds) composed by Frédéric Chopin. They were selected because the music notes were provided in the MIDI format[186], and were popular classical music which were characterized as relaxing music tracks having smooth, steady, and clear tempo. These two music tracks were presented in the intervention period alternatively in counter-balanced order to prevent participants from being bored. The sound volume was adjusted to appropriate level by each participant in advance.

The participants were guided to sit back in a reclined seat with closing their eyes throughout the experiment (Figure 17). They were instructed not to consume any food and beverages, except for water, within two hours before the experiment started. The experiment was conducted for two separate days with the order of condition counter-balanced.

Figure 17: Experiment protocol

3.3.3 Measurements

ECG and EDA were recorded by a bio-amplifier (MP150, BIOPAC Systems, Inc., USA) with 16-bit resolution and at 500Hz sampling rate. Electrodes for each measurement were placed under right clavicle and on lower left abdomen for ECG (so called "Lead II" induction) and the palmer side of the middle phalanges of the second and forth fingers of participants' non-dominant hand for EDA. The signal was filtered with a 35 Hz low pass pulse 50 Hz notch filter and 0.05 Hz low cut filter for ECG and 10 Hz low pass filter for EDA (MP150, BIOPAC Systems, Inc.).

From ECG, the HR and HF component of the HRV, which was determined as the frequency component in between 0.15-0.40 Hz of HRV for every one-minute time window, were calculated using a proprietary software for the bio-amplifier (AcqKnowledge® 4.1., BIOPAC Systems, Inc.). The ECG data obtained by the amplifier was used for the heartrate music feedback system as abovementioned.

EEG at Fz, C3, C4, Pz, O1, O2 with references (A1 and A2) by the 10-20 international system was recorded by another bio-amplifier (AP216, Miyuki Giken co. ltd., Japan) with 16-bit resolution and at 500Hz sampling rate (Figure 18). EEG signals were filtered with a high (60 Hz) and low (0.53 Hz) cut filter and 50 Hz notch filter. As for frequency domain analysis, alpha (8-12 Hz) and beta (13-30 Hz) power of EEGs were calculated for every one-minute time window using a proprietary software for the bio-amplifier (AP Viewer 4.12A, NoruPro Light Systems, Inc., Japan).

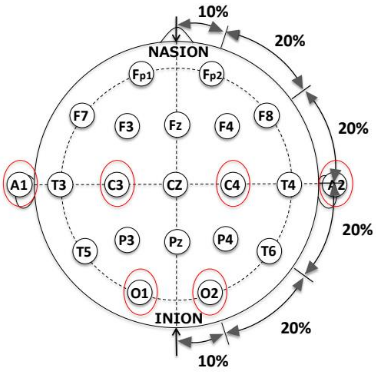


Figure 18: 10-20 electrode system

Respiration signal was obtained by a thermistor placed under nostrils (NXFT15H103, Murata Manufacturing co., ltd., Japan) using the same bio-amplifier with EEG with 16-bit resolution and at 500 Hz sampling rate. The respiration signal was filtered with a high (15 Hz) and low (0.05 Hz) cut filter. These physiological measures were obtained throughout the experiment (Figure 15).

In the context of psychophysiology, human factors engineering, and other related area, abovementioned physiological measures are referred to assess autonomous and central nervous system activity and interpreted in relation to psychological state[187]. For example, when we face an acute stressor, EDA and HR might increase and HF decrease; or when we are relaxing, EEG alpha power and respiration interval might increase, and vice versa. At the same time, it should be emphasized that such an interpretation is highly context-dependent and not necessary to consider as it can be solely and exclusively applicable.

As for subjective measures, a visual analog scale (VAS) for subjective feelings with two endpoints (0: do not feel so at all, 100: very strong feeling), comprising five items, “tension”, “fatigue”, “anger”, “confuse”, and “drowsiness” was given to the participants at the time points depicted in Figure 13. The VAS for “preference” of the music tracks (0: do not prefer it at all, 100: prefer it very much) was also given to the participants after the completion of two experimental conditions. In addition, the participants were asked about their familiarity with the given music tracks, and whether there was any difference in the music to which they listened on two experiment days (in either FB or CT condition).

3.3.4 Data analysis and Statistics

All physiological measures were standardized (z-score) and baseline corrected with respect to the average of the first minute of the initialization period owing to the large variation amongst individuals[188]. Following standardization, one-sample and paired t-test was performed for verifying changes from the baseline to the mean of subsequent period (Intervention or Rest 2) and for comparing those changes between the conditions, e.g., the change from the baseline to the mean of Intervention in FB was compared with that in CT. For the multiple comparison of EEG electrode locations, the p-values were corrected according to the Benjamini-Hochberg (BH) procedure.

For subjective measures, one-sample t-test was performed for verifying changes from the first (pre-Intervention) to the second (at the end of Rest 2) assessment for the five items of subjective feeling and difference from 50 (considered as fair) for “preference.” Likewise, paired t-test was performed for comparing of the changes (for subjective feelings) or the scores (for “preference”) between conditions. P-values less than 0.05 were considered significant.

There were no missing values in any of the measurements for all conditions and participants.

3.4 Results

3.4.1 Music tempo in FB condition

Figure 19 shows a typical change in music tempo (%) in FB condition for a participant. Although the profile of the change varied amongst participants owing to intra-individual interactive nature of the architecture presented in this study, music tempo fluctuated reflecting the heart rate variability as seen in the figure, whereas it was fixed to the original tempo (100%) in CT condition. The mean (SD), maximum, and minimum change in music tempo (%) in FB condition was 95.84 (2.97), 101.8, and 90.60.

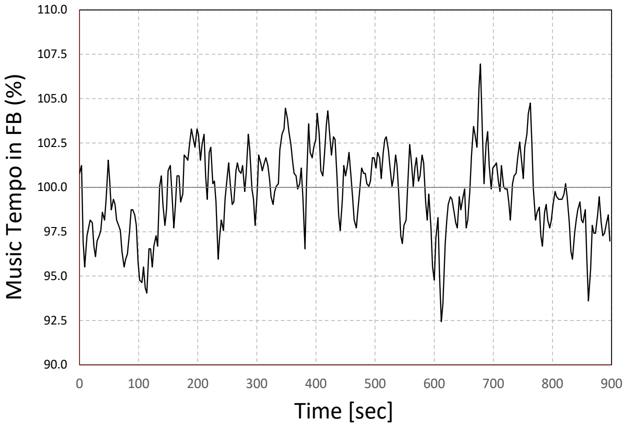


Figure 19:A typical profile of the change in music tempo (%) in FB condition

3.4.2 Physiological measures

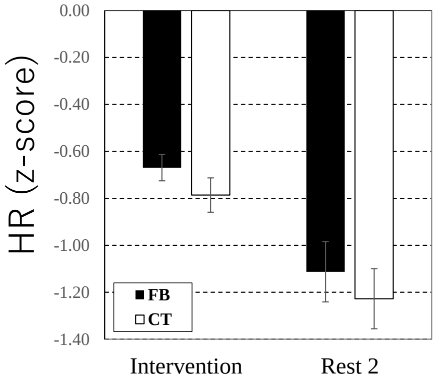


Figure 20: Mean (±SD) heart rate of the intervention and rest period

Figure 20 shows the mean (±SD) HR during the 15 mins of intervention and the subsequent 10 mins of rest period in two conditions. Note that the values were standardized as abovementioned (hereafter the same). Regardless of the conditions, HR decreased by listening to the music tracks in the intervention period (CT: $t_{10} = 10.9$, $p < 0.001$; FB: $t_{10} = 10.5$, $p < 0.001$) and it remained at a lower level in the subsequent rest period (CT: $t_{10} = 8.03$, $p < 0.001$; FB: $t_{10} = 7.26$, $p < 0.001$). There were no significant differences between the conditions in the intervention ($t_{10} = 1.78$, $p = 0.106$) and the rest period ($t_{10} = 0.57$, $p = 0.580$).

Figure 21 shows the mean (±SD) of HF component during the intervention and rest period. In CT condition, HF increased in the intervention period ($t_{10} = 5.85$, $p < 0.001$) and remained at a higher level in the rest period ($t_{10} = 2.82$, $p = 0.018$). Meanwhile, in FB condition, HF did not change significantly in both periods (Intervention: $t_{10} = 1.77$, $p = 0.106$; Rest 2: $t_{10} =$

0.25, $p = 0.811$). Comparing among conditions, the HF in FB condition in the intervention period was significantly lower than that in CT ($t_{10} = 3.28$, $p = 0.008$) whereas there was no difference in the subsequent rest period ($t_{10} = 1.33$, $p = 0.212$).

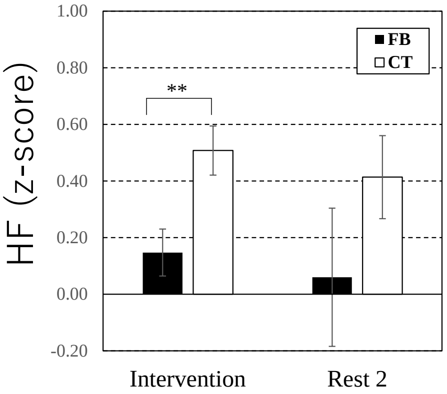


Figure 21:Mean (±SD) high-frequency component of heart rate variability of the intervention and rest period. ** p < 0.01 by comparison between conditions.

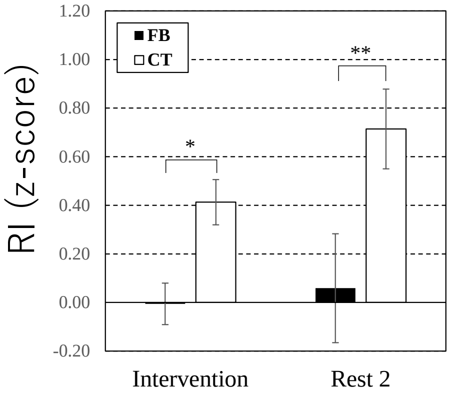


Figure 22:Mean (±SD) respiration interval of the intervention and rest period. * p < 0.05, ** p < 0.01 by comparison between conditions.

Figure 22 shows the mean (±SD) of the RI during the intervention and rest period. The RIs were obtained by peak-to-peak interval of the respiration signal. In CT condition, RI increased in the intervention period ($t_{10} = 4.08$, $p = 0.002$) and remained higher level in the rest period ($t_{10} = 4.02$, $p = 0.002$). Meanwhile, in FB condition, RI did not change significantly in both periods (Intervention: $t_{10} = 0.07$, $p = 0.948$; Rest 2: $t_{10} = 0.26$, $p = 0.800$). Comparing among conditions, the RI in FB condition in the intervention period and the rest period were significantly lower than that in CT (Intervention: $t_{10} = 3.12$, $p = 0.011$; Rest 2: $t_{10} = 3.53$, $p = 0.005$).

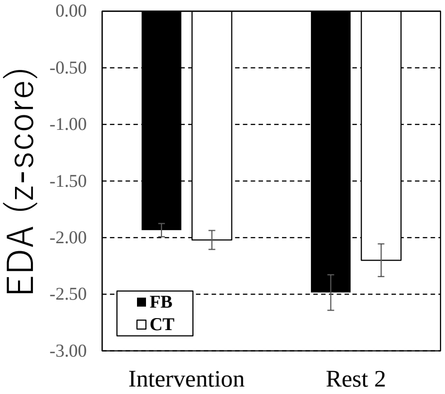


Figure 23: Mean (±SD) electrodermal response of the intervention and rest period

Figure 23 shows the mean (±SD) EDA during the intervention and rest period. Regardless of the conditions, EDA decreased in the intervention period (CT: $t_{10} = 24.0, p < 0.001$; FB: $t_{10} = 32.8, p < 0.001$) and remained at a lower level in the rest period (CT: $t_{10} = 15.3, p < 0.001$; FB: $t_{10} = 15.8, p < 0.001$). Comparing among conditions, there were no significant differences between the conditions in the intervention period ($t_{10} = 0.92, p = 0.378$) and the rest period ($t_{10} = 1.33, p = 0.212$).

Figure 24 shows the mean (±SD) of the alpha power of EEG at Fz, Pz, C3, C4, O1, and O2. Regardless of the conditions and location of the electrodes, the alpha power decreased in the intervention period and remained at a lower level in the rest period (Intervention CT: $p < 0.001$ for Fz, Pz, C3, C4, O1, and O2; Intervention FB: $p < 0.001$ for Fz, Pz, C3, C4, O1, and O2; Rest 2 CT: $p = 0.003$ for Fz, $p = 0.011$ for Pz, $p = 0.009$ for C3, $p = 0.004$ for C4, and $p < 0.001$ for O1 and O2; Rest 2 FB: $p = 0.018$ for Fz, $p = 0.031$ for Pz, $p = 0.003$ for C3, $p = 0.018$ for C4, and $p < 0.001$ for O1 and O2. Note that p-values were corrected according to BH procedure, and the same for hereafter). Comparing among conditions, there were no significant differences between the conditions in the intervention ($p > 0.05$ for Fz, Pz, C3, C4, O1, and O2) period.

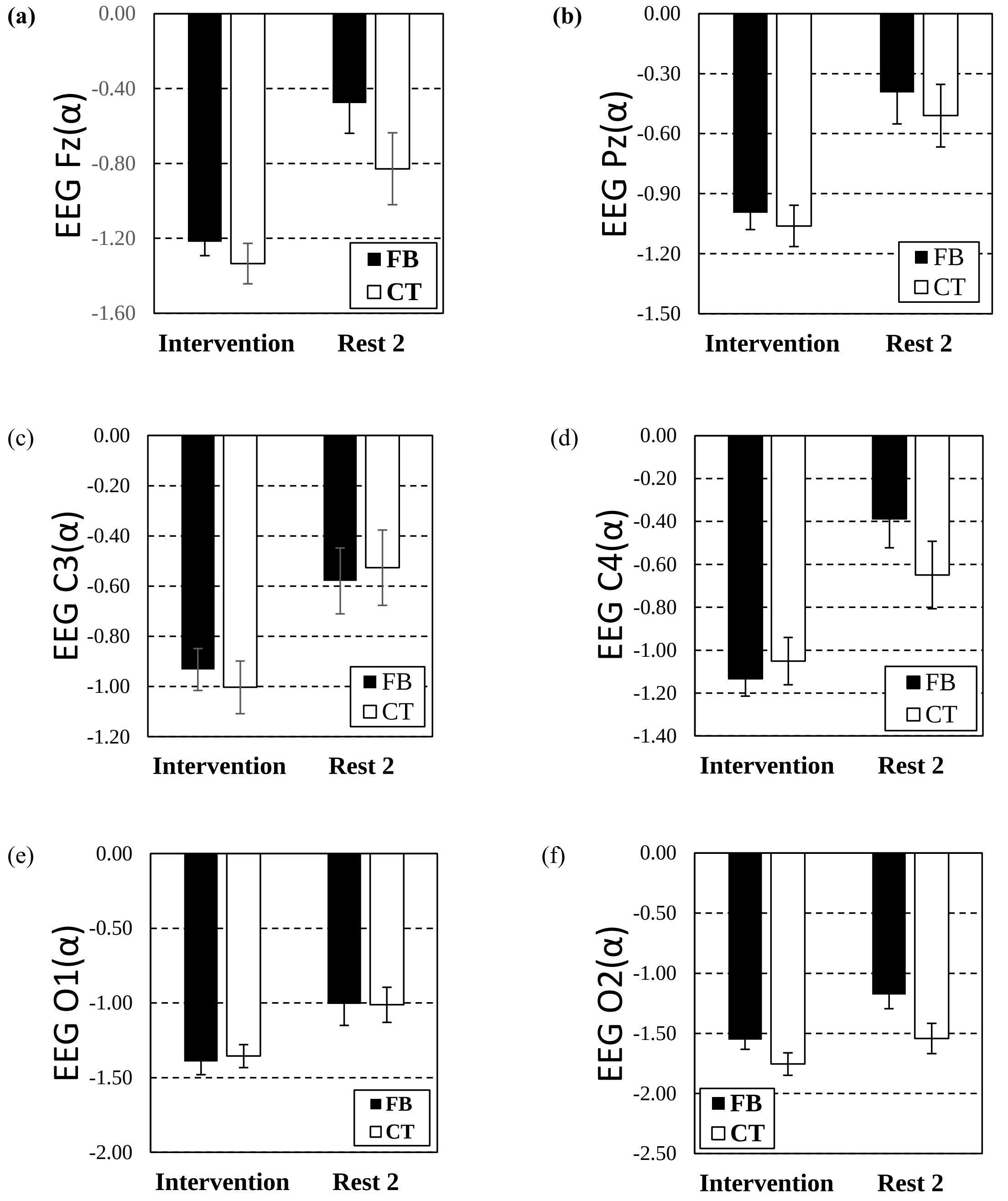


Figure 24: Mean (±SD) EEG alpha power of the intervention and rest period at (a) Fz, (b) Pz, (c) C3, (d) C4, (e) O1, and (f) O2. Note that, as only for Fz, the baseline correction was made with regard to 3 min at the initial rest period because of the large gap in initial 2 mins.

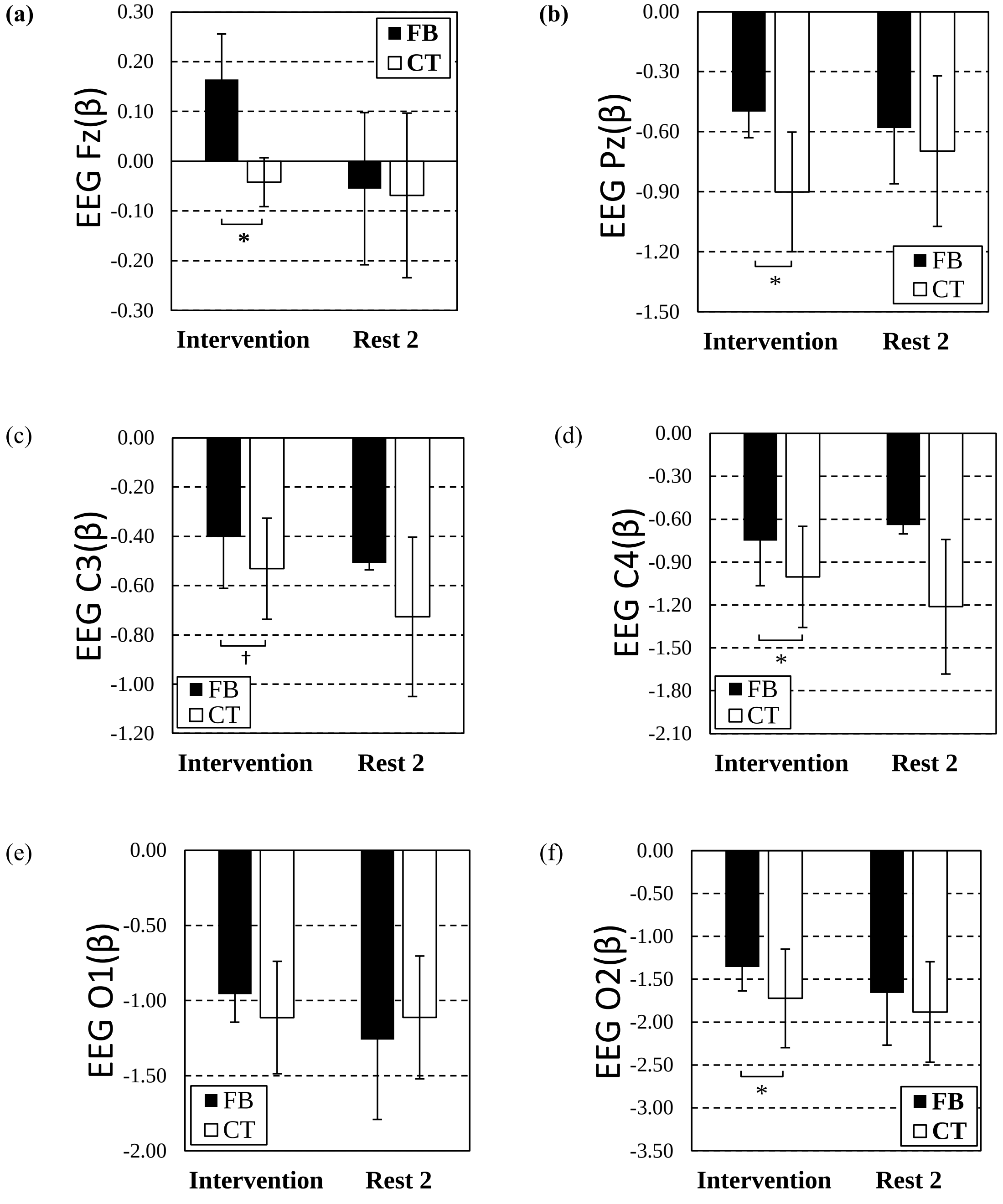


Figure 25: Mean (±SD) EEG beta power of the intervention and rest period at (a) Fz, (b) Pz, (c) C3, (d) C4, (e) O1, and (f) O2. * $p < 0.05$, † $p < 0.10$ by comparison between conditions. Note that p-values were corrected according to the Benjamini–Hochberg procedure.

Figure 25 shows the mean (±SD) of the beta power of EEG at Fz, Pz, C3, C4, O1, and O2. Regardless of the conditions and location of the electrodes other than Fz, the beta power decreased in the intervention period and remained at a lower level in the rest period (Intervention CT: $p < 0.001$ for Pz, C3, C4, O1, and O2; Intervention FB: $p < 0.001$ for Pz, C4, O1, and O2, p

= 0.005 for C3; Rest 2 CT: $p < 0.001$ for Pz, C3, C4, O1, and O2; Rest 2 FB: $p = 0.002$ for Pz, $p = 0.003$ for C3, $p = 0.002$ for C4, and $p < 0.001$ for O1 and O2). Comparing among conditions, the decrease of beta power in the FB condition was significantly, or on average at C3 and O1, smaller in the intervention period than those in CT ($p = 0.027$ for Fz, p = 0.015 for Pz, p = 0.051 for C3, p = 0.035 for C4, and p = 0.272 for O1, and p = 0.031 for O2).

Table 4: Mean (±SD) VAS scores for subjective items

Item	Condition	Before intervention	After intervention
tension	CT	13.2 (8.2)	9.5 (8.1)
	FB	15.7 (9.9)	8.3 (7.9) *
fatigue	CT	16.7 (16.1)	18.8 (9.8)
	FB	23.0 (20.0)	25.0 (16.2)
anger	CT	6.6 (8.3)	5.9 (6.7)
	FB	7.3 (10.5)	6.5 (8.1)
confuse	CT	6.5 (7.9)	6.5 (6.7)
	FB	10.2 (10.8)	9.1 (10.6)
drowsiness	CT	32.4 (19.3)	44.2 (24.0) *
	FB	40.8 (16.7)	45.7 (31.4)

* $p < 0.05$ by comparison within condition

3.4.3 Subjective measures

VAS scores for subjective measures are summarized in Table 4. Among these items, “tension” in FB and “drowsiness” in CT were significantly decreased ($t_{10} = 3.16$, $p = 0.010$) and increased ($t_{10} = 2.59$, $p = 0.027$), respectively. Comparing among conditions, the decrease in “tension” in FB tended to be larger than in CT ($t_{10} = 1.86$, $p = 0.093$). For others, there were no significant (nor tendency of) differences within and between conditions.

Table 5: Mean (±SD) scores for “preference”

Music track	Condition	Mean (SD)
Gymnopédies	CT	63.1 (8.8)
	FB	67.4 (17.4)
Raindrop	CT	69.5 (9.7)
	FB	71.3 (16.7)

Regarding the music tracks, both music tracks were preferred by participants (*Gymnopédies* CT: $t_{10} = 4.96$, $p = 0.001$; *Gymnopédies* FB: $t_{10} = 3.32$, $p = 0.008$; *Raindrop* CT: $t_{10} = 6.68$, $p < 0.001$; *Raindrop* FB: $t_{10} = 4.23$, $p = 0.002$), while there was no difference in the scores between conditions (Table 5). Six and two out of 11 participants replied as they were familiar with "*Gymnopédies*" and "*Raindrop*," respectively. Notably, no one found and claimed the difference in the music they experienced in FB and CT conditions.

3.5 Discussion

In this study, we implemented the heartrate music feedback system and tested its psychophysiological effect in a laboratory setting, where participants listened to the music in which the tempo of the music was continuously changed in accordance with their instant HR in a real-time manner. Compared with the CT condition, the HF component of HRV were significantly lower. In RI, there was no significant change from the baseline in the FB condition, and it was significantly lower compared with the CT condition. The beta power of EEG was significantly higher when listening to heartrate feedback music tracks (FB condition). Intriguingly, there were no distinct differences in subjective scores between conditions. Moreover, no participant claimed any difference in the music tracks in FB and CT conditions they experienced. This implies that the difference in the physiological responses between the conditions was derived not from perceptible or recognizable differences in music but from purely physiological functioning at unconscious level. To the best of our knowledge, no study has ever reported such phenomena found in this study; few studies implemented instant heartrate feedback music players in the first place.

Relaxation music alleviates and enhances sympathetic and parasympathetic nervous system activation. The reduction in HR and EDA, which reflect sympathetic nervous system activity, and the increment of HF, which reflects parasympathetic nervous system activity, observed in the CT condition are thus typical physiological responses induced by listening to relaxation music. Those responses in the heartrate feedback condition are in common regarding the alleviation of the sympathetic nervous system, i.e., reduction in HR and EDA and increase in HF. The reduction of alpha and beta power, regardless of the conditions, is in line with these autonomous nervous system responses as it may simply attribute to the lowering of the arousal level during and after intervention. It should be no surprise in the situation of our experimental setting where participants were instructed to listen to the music sitting back in a reclined seat with their eye-closed.

However, somehow the RI in the FB condition did not show any change from the baseline, resulting in a remarkable difference from that in the CT condition. Further, such a difference in respiration presumably induced the difference in the HRV in terms of HF by the nature of respiratory sinus arrhythmia.

Table 6: Changes in EEG beta wave activity

Study	Participant	Intervention	Findings
[193]	8 normal volunteers	Rest and listening to music	Listening to music caused a significant increase in beta power
[194]	10 non-musicians	Two genres (rock and jazz) and three tempos (slowed, medium/normal, and quickened)	Beta wave amplitude increased significantly as the tempo increased
[195]	18	Listening to favorite relaxing music, and stimulating music , with and without stimulation on the foot	Beta activity increased during activating music and tactile stimulation for most participants.
[196]	3 females and 9 males	(1) Resting (2) Listening to acoustic stimuli (3) Mental tasks under quiet environment (4) Mental tasks under acoustic stimuli	The beta wave is rarely affected by the acoustic stimuli and mental arithmetic
[197]	Experimental group (28), control group (27)	The experimental group participated in 13 more group music therapy sessions over 7 weeks than the standard group.	No significant decrease in beta waves was found in the two groups.
[198]	22 females and 11 males	Listening to binaural beats tone of 10Hz	Participants' Beta brainwave decreased

At this moment, it is not clear what kind of pathway involves in the top-down regulation of respiration and following HRV variation by listening to such unusual and bizarre heartrate feedback music tracks. Empirically, music or musical stimuli evokes the desire to move and is accompanied by brain activity in the motor cortex[190]. Thus, the music's tempo change may influence motor-related brain activities. Table 6 shows the changes in EEG beta wave activity from previous studies. The effect of listening to music on beta waves varied from study to study. In this study, participants lay on a stool and listened to music without moving. It cannot be definitively concluded that the reduction in beta wave activity is attributed to motor-related processes. Moreover, Fujioka et al. (2015) demonstrated in their magnetoencephalography study that the beta-band oscillation related to musical meters[199]. In our study, we observed the distinct and widespread difference in the beta power between FB and CT conditions. Although we cannot assume a direct linkage between the study [199]and our results, there might be an involvement of specific brain activation in the top-down regulation of the phenomena we found in our study. However, it should be emphasized that it is still unknown how such regulation occurred at unconscious level of the processing; no participants report any difference in the music tracks in FB and the CT. Further neurological study is needed to reveal the underlined neurological pathway for this point.

Participants in this study were all male university students. The main limitation of this experiment was the relatively small number of participants and the absence of female participants. Similar to the study above, wired instruments that measure physiological indicators may cause discomfort or a sense of restraint in participants. In future studies, wireless instrument measurements will be used.

3.6 Chapter Summary

In this part, a heart rate music feedback architecture was developed by installing a MIDI interface connected to a bio-amplifier and tempo control interface. Additionally, the psychophysiological effects of the architecture were explored. Compared with the control condition, significantly lower RIs, HF component of the HRV, and a higher beta power of the EEG were observed. Moreover, there were no distinct differences in subjective scores and impressions of the musical experience. These results imply that the difference in physiological responses between the conditions may be derived not from perceptible or recognizable differences in music but from purely physiological functioning at unconscious level.

CHAPTER 4

STUDY ON HUMAN PULSE WAVE DETECTION

This chapter introduce a novel approach to measure human pulse using consumer-grade headphones and headsets. The structural equivalence between dynamic driver headphones and those equipped with both headphones and microphones provides the foundation for this innovative methodology. Furthermore, as electronic devices, these audio equipments have the capability to detect sound frequencies below the threshold of human auditory perception. Building upon this principle, our research endeavors to propose a straightforward method for pulse measurement through signal separation, capitalizing on the pressure variations induced within the ear canal and around the earpad by each heartbeat.

In the forthcoming sections, an in-depth examination of the architecture, experimental measurement and discussion of this approach will be undertaken.

4.1 Earphone-type health monitoring

Both techniques of respiratory control and relaxation music biofeedback rely on the monitoring of HR. With the progression of technology, the practice of HR monitoring has transcended its initial confinement to clinical settings. Everyday devices, such as smartwatches, HR belts, and intelligent headphones, now enable the continuous tracking of HR in routine life. Earphone-type health monitoring refers to wearable devices that are designed to be worn in or around the ears and offer various health monitoring capabilities. These devices have gained popularity due to their convenience and potential benefits.

According to a WHO survey [200], cardiovascular diseases are the leading cause of death worldwide, and second only to cancer in Japan[201]. Since cardiovascular diseases are associated with lifestyle[202], it is important to monitor cardiovascular function daily in order to assess mid- to long-term morbidity risk. Wristwatch health monitoring devices, which are currently undergoing remarkable development (e.g., Fitbit)[203-206] are ideal for this purpose. These devices can evaluate a person's HR continuously 24 hours and 365 days with only a short charge of about 30 minutes a day, and the data can be accumulated and visualized on the cloud. Wearable devices that can evaluate autonomic nervous system functions other than HR, such as

Galvanic Skin Response, are also on the market[207,208].

HR monitoring wearable devices come in various forms, including smartwatches, fitness trackers, chest straps, headphones, and more. There are some disadvantages to wristwatch devices. Tattoos can affect HR accuracy: many manufacturers highlight that having tattoos on the wrist can disrupt HR monitoring. Apple, for instance, states that the ink, pattern, and saturation of certain tattoos may obstruct the light sensor, leading to unreliable readings. Garmin also acknowledges that tattoos can block light, potentially making it challenging to obtain accurate heart rate readings, causing either inaccuracies or a complete lack of readings. Cost of smartwatches: smartwatches can be expensive, and some individuals may be unwilling to make such an investment. Lack of wearable habits: additionally, not everyone is accustomed to wearing a watch or fitness tracker regularly. These factors contribute to a diverse landscape of challenges in HR monitoring, including physical hindrances like tattoos, financial considerations, and individual preferences regarding the habit of wearing wrist-based devices. As technology advances, addressing these challenges will be crucial to ensuring widespread and accurate HR monitoring for users with varying lifestyles and preferences.

By using these devices, research results from measuring HR in daily life, which were not previously available, have been reported. For examples, Lubitz et al. (2022) developed an algorithm for detecting undiagnosed atrial fibrillation based on Fitbit-measured PPG[209]. Jiang et al. (2019) employed a wristwatch-type HR monitor for investigating physiological effects of citrus aroma during sleep at home: the wearable device enables researchers to conduct an experimental sleep study in a home environment[210].

With advancements in technology, portable health monitoring devices have evolved beyond wristwatch-type products to include earphone-type ones as well. These versatile devices now serve the dual purpose of wearable health monitoring and music listening. Amazfit PowerBuds Pro[211] is one such versatile device that uses an optical sensor built into the earphone head to measure pulse waves. These devices, including the wristwatch type, use the pulse plethysmography (PPG) method to capture the changes in peripheral blood vessel volume that occur with heartbeats. Although there have been reports of inaccuracy during exercise due to problems with the adhesion of the contact surface, the pulse wave can be measured accurately when the patient is at rest[212-214]. However, these products require specific devices and applications, leaving users with little choice regarding their preferred earphones/headphones. Existing earphone-type monitoring devices encounter several challenges. Firstly, these products often necessitate specific devices and applications, limiting users' choices when selecting their preferred earphones. Additionally, there are compatibility issues, as these devices may have limitations tied to particular platforms or devices, further restricting users who prefer different operating systems. Another concern involves battery life, with users frequently needing to recharge their earphones, impacting the convenience and continuity of HR monitoring. Lastly, during intense physical activities or rapid movements, earphones may struggle to provide accurate HR readings, introducing challenges to the reliability of the monitoring data. Addressing these issues is crucial for improving the overall functionality and user experience of earphone-type HR monitoring devices.

HR/HRV sensing using consumer products is necessary. Fluctuations in HR and HRV serve as crucial indicators of various health conditions, encompassing stress, fatigue, and cardiovascular issues. A growing number of consumers leverage HR and HRV data to fine-tune their fitness regimens. One advantage lies in the early detection of health issues. While consumer-grade devices cannot replace the precision of medical-grade monitoring, they function as proactive alert systems, prompting users to seek professional medical advice upon detecting significant deviations. The integration of HR and HRV data into consumer devices not only enriches user engagement but also serves as a catalyst for behavioral change. The ability to access real-time data and discern trends acts as a motivational force, inspiring individuals to maintain an active lifestyle, make healthier choices, and persevere in their pursuit of fitness and wellness objectives.

Moreover, the algorithm used to calculate HR from PPG remains undisclosed. Most products only display average HR over time and cannot display instantaneous HR. A few products offer HRV readings[215,216], which can help represent cardiac autonomic nervous system activity[217]. However, it is still unclear how they calculate HRV since the raw waveform of PPG is not always disclosed.

In addition, the algorithm for how the HR is calculated from the PPG waveform, which may vary depending on the physical shape and electronic circuit characteristics of the measurement device, has not been disclosed: most products only display the average HR over minutes, not the instantaneous HR. Some of these products have a function to display HRV, which in some sense may be more important psychophysiological index than HR, as such it represents cardiac autonomic nervous system activity; However, since the raw waveform of PPG is disclosed, it is unclear how they calculate HRV.

In contrast, as discussed below in the next section, we propose a new method of human pulse measurement architecture using ordinary earphones and headphones. It is a simple signal separation-based method utilizing pressure changes inside the ear canal caused by heartbeats. Although this is a completely different methodology from PPG, it is promising because 1) HR can be measured while listening to music (this is the same as the aforementioned products using the photoelectric pulse wave method), 2) it is feasible for almost all of the consumer earphones and headphones, 3) the peak-to-peak interval can be accurately and continuously collected, enabling accurate measurement of HRV in the format that allows access to raw data, and 4) when the frequency characteristics of the earphones/headphones used are known in advance, the raw pulse waveforms can be reproduced that would have clinical significance.

4.2 Architecture

4.2.1 Overview of Pulse Pressure Wave Measurement

The following is an overview of the pulse wave measurement method using earphones and headphones proposed in this study. An earphone is a device that converts electrical signals into sound waves (pressure waves) by means of diaphragm vibration, which is the same structure as a dynamic microphone except that the signal conversion direction is the exact opposite. In other words, earphones can be used as microphones. Earphones are designed to reproduce sound sources in the human audible range of 20 Hz to 20 kHz, but they can also reproduce (or in this case, “record”) vibrations in frequencies lower than the audible range. For example, the Electret Condenser Microphone has a so-called "stiffness control" that theoretically ensures constant sensitivity in the low-frequency range[218,219]. Therefore, by using the characteristics of the earphone as a microphone, pulse waves with a center frequency of 1.4 Hz caused by heartbeats can be measured via changes in internal pressure in the ear canal (Figure 26).

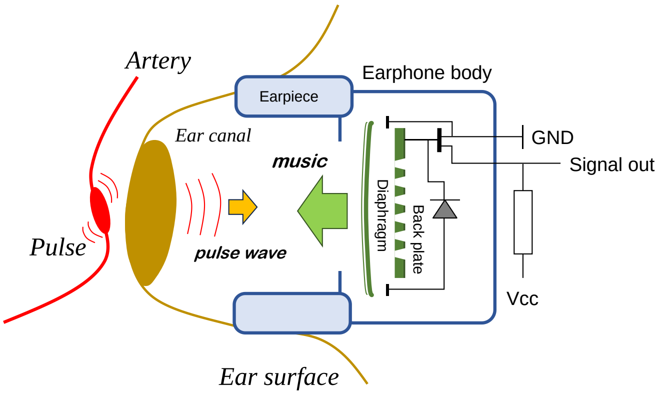


Figure 26: Basic principle of this research method: diaphragms built into earphones can capture pressure changes in the ear canal caused by human heartbeats.

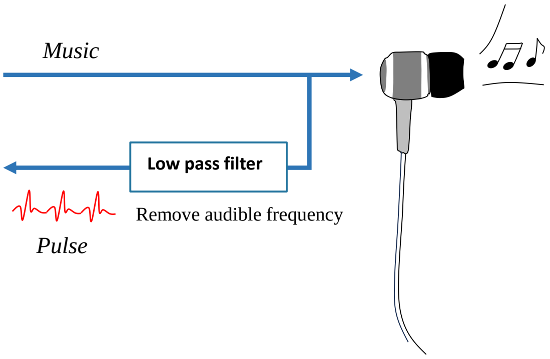


Figure 27: Conceptual diagram of filter settings for pulse wave collection.

Moreover, even while music is being played, that is, while sound waves are being presented to the user by the vibration of the diaphragm, the diaphragm inside the earphone captures changes in the internal pressure of the ear canal concurrently, due to the "principle of superposition" of the waves. Therefore, the pulse wave signal can be obtained by low-pass filtering the electrical signal (induced by the diaphragm vibration), in which the pulse wave signal should be superimposed on the music signal (Figure 27). In addition, the same principle can be applied to headphones to capture the pressure pulse derived from the pulsation of arteries around the tragus.

Figure 28 shows the pulse wave data measured during music presentation. The earphone used for the measurement is an in expensive sealed dynamic earphone (SHE3590, Koninklijke Philips N.V.). Electrical signals (music and pulse) were measured by a data logger (PicoScope

4424, Pico Technology) with a sampling frequency of 100 kHz. The background music was *String Quartet No.17 in B-flat major K.458 "Hunt"*, W.A Mozart. Pulse wave signals were separated by a lowpass filter with a cutoff frequency of 10 Hz. As shown in the figure, while music is being presented to the user, the pulse pressure wave accompanying the user's heartbeat can be monitored at the same time. The peak-to-peak interval (PPI) of the pulse wave signal is also clear, and therefore the instantaneous heart rate can be measured accurately and continuously, enabling proper evaluation of HRV. However, the waveform of the recorded pulse pressure wave differs from that of the PPG because it has differential characteristics due to the frequency characteristics of the earphones/headphones used, as described next.

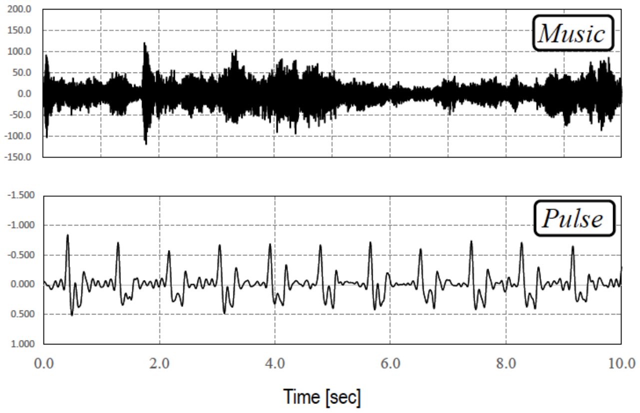


Figure 28: Pulse wave recorded by a consumer earphone.

4.2.2 Feasibility evaluation

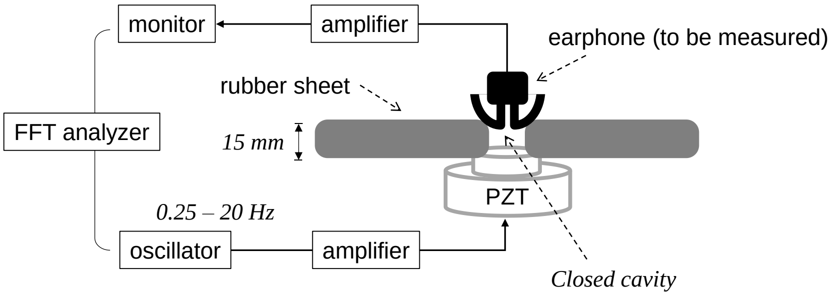


Figure 29: Pulse wave recorded by a consumer earphone.

Pulse waves can be used to evaluate autonomic nervous system function by deriving HR and HRV. In addition, the pulse waveform itself also has clinical significance. Sano et al. classified the waveform patterns of accelerated pulse wave, which is the second-order differentiation of PPG, into seven types and suggested their relationship to aging and cardiovascular diseases[218]. However, since any pulse pressure wave is recorded through a physical sensor element, the waveform is distorted due to its electrical characteristics. Since the consumer dynamic earphones and headphones are electromagnetic induction systems, a differential element is added in the frequency band up to the resonance frequency when the earphones/headphones are used as microphones. In fact, Nomura et al. obtained frequency characteristics for a micro-electromechanical systems (MEMS) microphone and showed that it has first-order differential characteristics in the low frequency range of the heart rate's central frequency (around 1.4 Hz)[219]. It is highly possible that the consumer earphones/headphones targeted in this study also have similar frequency characteristics structurally. Therefore, we measured the frequency characteristics of the earphones/headphone in the low frequency range (0.25-20 Hz) including the center frequency of the heart rate using an evaluation apparatus with PZT speakers and FFT analyzer (CF-7200, ONO SOKKI co., ltd.) (Figure 29). As a result, as shown in Figure 30, it was confirmed that an earphone/headphone had a first-order differential characteristic of approximately -20 dB/dec near the frequency of interest as theoretically expected.

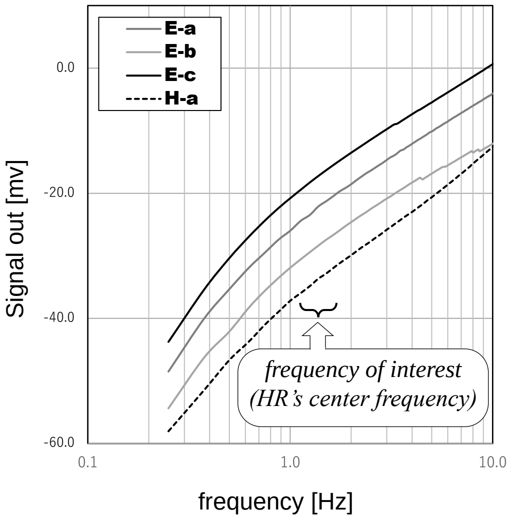


Figure 30: Frequency response of consumer three earphones and a headphone. E-a, E-b, and E-c represents three consumer earphones and H-a represents a consumer headphone.

In addition to the frequency characteristics of earphones/headphones, another possible cause of distortion of the collected signal is the effect of air leakage. When earphones are worn in the ear, it is impossible to seal the ear canal completely (even more so with headphones), so the differential characteristics associated with this air leakage are added to the collected signal. In other words, the pulse pressure wave signal collected by earphones/headphones should physically be a second-order differential waveform (accelerated pulse wave).

As mentioned above, this acceleration pulse wave is considered to contain clinically significant information and is meaningful in its original form. On the other hand, when it is necessary to observe undifferentiated pulse waveforms such as PPG, it can be derived from the acceleration pulse wave by taking this differential characteristic into account in advance. Figure 31 shows the acceleration pulse wave measured from a headphone and the velocity pulse wave and pulse wave derived from its integration.

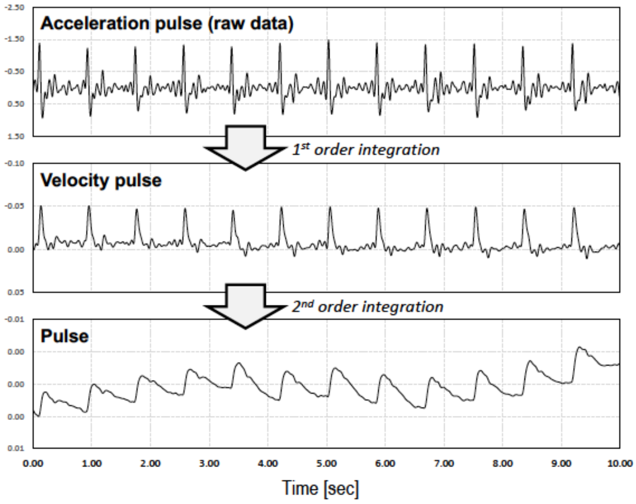


Figure 31: Velocity and pulse waveform reproduced by integration of acceleration pulse wave (raw data).

To evaluate the accuracy in pulse wave determination, the correlation between R-waves interval, or R-R interval (RRI), derived from ECG and the peak-to-peak interval (PPI) derived from consumer earphones/headphone was examined. The Ethics Committee of Nagaoka University of Technology approved the following experiment.

Table 7: Earphone and headphone information

Type	Manufacturer	Model	Frequency response
Earphone	Harman/kardon AE	AE	16Hz-20khz
Earphone	Philips	SHE3595	Entry: 12-23,500 Hz.
Earphone	Sony	XBA10(balanced armature)	5-25,000 Hz
Headphone	Yamaha	HPH-M82	20Hz～20 k Hz

The ECG and pulse waves from three consumer earphones and one headphone were recorded with 10 healthy adult males (mean age ± standard deviation: 22.1 ± 1.58) during 1) sitting rest and 2) light exercise on an ergometer, while classical music was presented through the audio devices. Music signal, ECG, and pulse waves from right and left ear were obtained by a bio-signal amplifier device (MP150, BIOPAC Systems, Inc. USA) with 16-bit resolution and at 5kHz sampling rate. The pulse wave signals were separated by an analog circuit with a low-pass filter with a cutoff frequency of 10 Hz and recorded by a bio signal amplifier. The RRI and PPI for pulse wave was obtained by dedicated software (Acknowledge 4.1, BIOPAC Systems, Inc.). The mean heart rate ± standard deviation for both conditions was 80.3 ± 10.5 [bpm] for sitting at rest and 95.1 ± 12.7 [bpm] for the ergometer exercise, respectively.

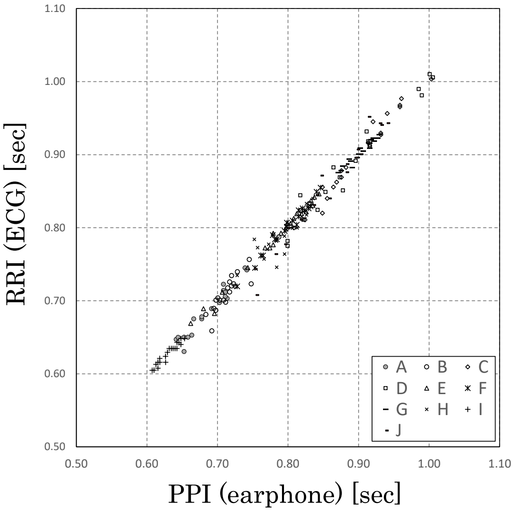


Figure 32: Correlation between RRI derived from ECG and PPI derived from an earphone. Each symbol (A-J) represents the data of each participant.

Figure 32 shows the correlation between the RRI derived from ECG and PPI derived from a consumer earphone. Each symbol in the figure represents the RRI and PPI of 20 consecutive beats of each individual while at rest in the sitting position. As shown in the figure, the PPI taken from the earphones has a high correlation with the RRI. Table 8 shows the correlation coefficients between RRI and PPIs for the right and left ears of three earphones and one headphone. The strong statistically significant correlations were observed for each audio device regardless of condition ($p < 0.001$ for all). The correlation coefficients tended to be larger in the sitting-at-rest condition than in the ergometer condition, although the differences were not statistically significant.

Table8 : Correlation coefficients determined from three consumer earphones and one headphone with right (R) ear and left (L) ear. "Rest" and "Cycle" represents the data obtained while sitting at rest and during light exercise with an ergometer, respectively.

		Rest		Cycle	
		Mean	S.D.	Mean	S.D.
Earphone A	R	0.903	0.086	0.887	0.078
	L	0.925	0.062	0.886	0.059
Earphone B	R	0.974	0.029	0.856	0.289
	L	0.921	0.101	0.875	0.141
Earphone C	R	0.953	0.058	0.903	0.108
	L	0.968	0.034	0.916	0.084
Headphone A	R	0.943	0.067	0.954	0.057
	L	0.956	0.057	0.948	0.034

4.3 Discussion

This study reports on a method for measuring human pulse waves using ordinary earphones and headphones by utilizing pressure changes inside the ear canal caused by heartbeats. Although this methodology is completely different from mainstream products using the photoelectric pulse wave method, it was demonstrated that heart rate can be measured while listening to music by using appropriate signal separation. As shown in the evaluation test, the correlation with the ECG is also high, and thus the heart rate can be measured accurately.

The earphones/headphones may detect the vibration of the body that the heart generates. However, since the diaphragm, which detects the external signal, is fixed to the earphone/headphone housing, the diaphragm cannot independently capture body vibrations as the housing vibrates at the same time. It is confirmed by the fact that the measured Pulse waveform (Figure 28) has the same shape as PPG.

It should be noted that the correlation coefficient is higher during sitting-at-rest than during exercise, although the difference is not significant. This is probably due to the greater heart rate variability during sitting than exercise, rather than to differences in the precision of pulse pressure measurement. In other words, the average heart rate is higher during exercise than during sitting-rest, and the suppression of parasympathetic nervous system activity associated with exercise results in smaller "intra-individual" heart rate variability. Therefore, the data variability is inevitably smaller during exercise, so the correlation coefficient can be relatively lower than during rest.

The greatest advantage of method in the present study is that, because it is a software-based pulse wave derivation technique, it can be implemented in all consumer earphones and headphones, unlike the photoelectric method. The user is free to choose the music presentation device to be used for this purpose. Voropai et al. have recently proposed a heart rate monitoring system that can be mounted on consumer headphones[221]. However, the system uses a dry contact conductive textile to record ECG, so it is practically a small bio-amplifier externally attached to the headphones.

In contrast, our approach requires a small and low-cost analog circuit, which is practical for real-life applications. The circuit is composed of two parts: 1) an analog filter (low-pass filter with a cutoff frequency of 10 Hz) to extract the pulse signal from the counter-electromotive force (signal) due to diaphragm vibration and 2) an IC amplifier to amplify the extracted pulse signal to a level that can be received at the microphone input of the mobile terminal or smartphone. Therefore, it could be designed as a small analog circuit (not exceeding the size of a button battery) consisting of resistance, capacitor, amplifier integrated circuit, and button battery. It should cost less than several hundred JPY. By inserting this analog circuit between the earphone/headphone jack and the audio jack of the mobile terminal, it is possible to observe pulse waves on the terminal, making it a convenient and cost-effective solution.

This method has two other advantages. First, since this method can accurately and continuously collect peak-to-peak intervals, it can accurately measure HRV, especially its high-frequency component (0.15-0.40 Hz), which is a reliable and important metric for parasympathetic nervous system activity[217][222]. Some wearable devices on the market claim to be able to measure HRV (e.g., Garmin[215]), but how it is achieved in a wearable device has not been disclosed; generally, a sampling frequency of 250 Hz or higher is required for accurate assessment of HRV, but as far as we confirm, the available HR data from the wearable device is limited to every second at the minimum[223]. It should be noted that precise evaluation of physiologically meaningful HRV requires a measurement system with high temporal and spatial resolution, and this is also true for our method. The fact that our method allows accurate measurement of PPI does not guarantee that HRV measurement can be implemented in wearable devices; it is strongly dependent on the performance of the device itself.

The second advantage is the ability to reproduce the raw pulse wave and velocity waveforms when the frequency response of the earphones/headphones is given, as shown in Figure 27. As suggested by Sano et al., pulse waves change with aging and cardiovascular disease, and therefore observing their waveforms has clinical significance[220]. In this case, however, the waveform changes due to changes in the physical properties (hardness) of the artery, so our method, which can measure pulse pressure directly, should be more suitable for this purpose than photoelectric pulse wave. In fact, Nomura et al. showed that in a pulse measurement system using MEMS microphone, the features for waveform classification, which is done by the arrangement of peak values of second derivative waveforms, are more distinct than in PPG[219]. As far as discussing clinical significance based on acceleration pulse wave as in the previous studies, it is not necessary to reproduce the original waveform because the derived “raw” waveform is already a second-order differential form in our method. However, it is not clear if one can equate pulse pressure changes observed in the external auditory canal (or around the tragus with a headphone) with those observed at the wrist by the pulsation of radial artery. To advance our understanding of the subject matter, it is imperative that we conduct additional clinical studies. This should include validating the methodology with a more diverse sample of participants across different age groups, genders, body mass indices, and health conditions.

Finally, a significant limitation to our method should be mentioned. Since the method captures low-frequency pressure changes with consumer audio devices worn on the head, accurate pulse wave measurement cannot be performed during exercise that includes large head vibration; this does not apply to lower body exercise with little head vibration, such as during light exercise with an ergometer. This is a limitation due to the loss of adherence of the earphones/headphones. Artifacts generated by body movement are a common and unavoidable problem not limited to our methodology but to other earphone-type and wristwatch PPG measurement devices and, ultimately, ECG measurement. It is necessary to select canals that fit the individual's ears, or to introduce a dedicated fixation method such as hearing aids during exercise. In the future research, we aspire to make progress in three areas. Firstly, we will customize devices to accommodate varying ear canal sizes, ensuring a secure fit. Secondly, factors like the intensity of physical activity and perspiration may cause headphones to loosen, potentially impacting the precision of our measurements. In the realm of sports headphones, designers are currently exploring ways to securely fasten headphones during high-intensity exercise. This is also a concern we aim to address in our upcoming efforts. Finally, this study was conducted in a resting state. In the future, we intend to broaden our inquiries to encompass various states, including resting, walking, running, and even boxing, to cater to the diverse needs of different populations.

4.4 Chapter Summary

This section we reported a method for extracting pulse waves embedded in the electric signals obtained from earphones/headphones. Since this method directly captures pulse pressure changes, it could capture more clinically relevant waveform information than PPG, which captures pulse waves optically. Furthermore, this method can be used with consumer devices, making it appeal to a wider range of users. For example, in situations where concentration needs to be assessed during e-Learning, our method can be implemented on an application basis without the need to purchase a new device; hemodynamic evaluation has been shown to be effective in such a situation[224]. Future clinical studies to investigate the clinical significance of pulse wave information and its application in various situations are needed.

CHAPTER 5

GENERAL DISCUSSION

The motivation behind this study is to underscore the significance of seamlessly integrating biofeedback technologies and devices into domestic settings without imposing undue cognitive demands or effort. The study aims to investigate the effects of posture displacement, evaluate the influence of feedback on respiration, and develop a proprietary bio-signal interactive music feedback architecture. Furthermore, innovative methods for measuring human pulse using consumer-grade earphones and headphones will be introduced.

5.1 Summary of Research

The purpose of this study was to investigate the developed biological feedback system involving posture-respiration and heart rate-music feedback, as well as the novel human pulse wave detection. In pursuit of this objective, three distinct experiments were conducted. The first study focused on the respiration-posture feedback, aiming to investigate the impact of posture displacement and the effect of feedback on respiration. The second study delved into heartrate music feedback, the results suggest that the physiological responses' disparity between conditions may arise from unconscious physiological processes rather than perceptible musical differences. Finally, the third study centered on the evaluation of the Earphone-type health monitoring device, examining its effectiveness in monitoring HR.

Four lifting height conditions were examined: 0.5 cm, 1 cm, 3 cm, and 6 cm in the respiration-posture feedback study. The 1 cm condition showed higher RI than the 3 cm condition and lower HR than other conditions. Additionally, the 3 cm condition exhibited higher in HF compared to the 1 cm condition. Notably, the 1 cm condition had a significantly higher in LF compared to the other conditions. Alpha wave components in areas C and O increased significantly in the 1 cm condition compared to the 3 and 6 cm conditions. The system demonstrated greater effectiveness in lengthening and deepening respiration under the 1 cm intervention condition.

The HR music feedback study consisted of two conditions: FB and CT. Significant differences were observed among conditions in RIs, HRV, and beta power of brain waves compared to CT. However, subjective scores and impressions of the musical tracks did not show discernible disparities. These findings suggest that variations in physiological responses between conditions may be due to unconscious physiological processes rather than perceptible differences in the music.

This signal separation-based approach utilizes pressure changes in the ear canal and around the tragus induced by heartbeats. Feasibility evaluation using ECG demonstrates the earphone/headphone-derived pulses are highly accurate in peak-to-peak determination. Additionally, we assessed the frequency characteristics of the audio devices at the HR center frequency (around 1.4 Hz), ensuring the reproduction of the original pulse waveform without distortion. Despite methodological differences from PPG, this approach holds promise for HR measurement during music listening.

5.2 Contribution

Technology plays a crucial role in enhancing a healthy lifestyle. When combined with biofeedback, it empowers individuals to improve their self-regulation abilities, ultimately benefiting their mental well-being. This study initially explores the physiological and psychological advantages of breath control and voluntary breathing methods. It subsequently addresses the positive impact of soothing music, followed by an examination of the benefits offered by health monitoring technology through consumer-grade earphones and headphones. Building upon these foundations and rationales, this research introduces the respiration-posture feedback system, a HR music feedback framework, and a methodology for pulse measurement using consumer-level earphones and headphones.

The respiration-posture feedback system presents a significant potential contribution in the development of medical devices aimed at assisting patients with respiratory conditions in conducting clinical treatments involving involuntary deep breathing. The system's adaptability allows for seamless integration into both commercial and home-use massage beds. By integrating the feedback system into a massage table designed for home use, people can receive respiratory support in the convenience and comfort of their own home. This not only reduces the burden on healthcare providers but also enables patients to take an active role in daily respiratory health management, potentially reducing the frequency of doctor visits and improving long-term health outcomes. For individuals dealing with respiratory conditions, the system has the potential to significantly enhance their quality of life. Garcia-Hernandez designed an innovative handheld mouth pressure biofeedback system for assessment and personalized game-based training of respiratory muscle strength. Results revealed that participants rated the system's overall usability as excellent. Furthermore, patients involved in the home training program showed a 40% increase in their Maximal Inspiratory Pressure (Pimax). It can be used to investigate new and effective training protocols that improve respiratory muscle performance[225]. By facilitating improved breathing techniques and relaxation, it may lead to reduced symptoms (shallow breathing) and an overall better sense of well-being.

Few studies have, in fact, implemented instant HR feedback music players prior to this research on the HR music feedback architecture. This technological advancement provides a method for synchronizing music tempo with the user's HR, resulting in an interactive music experience. The contributions of this study can be summarized as follows: First, people can easily use it at home without any professional knowledge of the system. Second, when using devices, people can freely play their favorite music.

The methodology for pulse measurement using consumer-level earphones and headphones holds promise due to its unique capability to measure HR seamlessly while individuals listen to music. Additionally, its affordability, aligning with standard consumer pricing, enhances its accessibility. The method's compatibility with widely available consumer-level earphones and headphones further extends its reach. This innovation exhibits versatility, finding applications in both medical care monitoring and daily physiological tracking within a home environment. Smartwatches are capable of tracking heart rate metrics, and researchers have found that their use shows promise in detecting heart disease (running algorithms to detect atrial fibrillation) and movement disorders[226]. Its potential to seamlessly integrate into everyday life sets it apart as a convenient and practical tool for monitoring HR in various settings.

CHAPTER 6

CONCLUSION

Our studies solidify the objective of seamlessly integrating biofeedback technologies into home environments without excessive cognitive demands or effort. Through a series of experiments, we have significant insights and introduced a new method. The respiration-posture feedback system revealed its potential impact on prolonging participants' respiration, offering a method for the regulation of the autonomic nervous system. The system is more effective under the 1cm body posture intervention condition. It has the potential as a consumer product to promote long-time deep breathing in the home environment. The potential of heartrate music interaction system as a means of influencing psychophysiological states opens avenues for further exploration and potential applications in areas such as home relaxation therapy and stress management. Users do not need to have any knowledge about music feedback systems and can use them directly in the home environment. Moreover, the headphones equipped with our human pulse measurement exhibit no device restrictions, making it easy to measure HR.

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