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PHD DISSERTATION

Entrainment Promoting Robot Based on Physiological Signals towards Human Cooperation

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Abstract

Entrainment has been studied for many years, which is a kind of lubricating oil in human-human interaction. A good interaction needs entrainment, which includes speech entrainment, body movements entrainment, and even entrainment between heart rates or brainwaves. Movements and speeches, which have been used for monitoring entrainment in conventional research, are self-controllable. However, these are unsuitable for monitoring the internal state of humans. Hence, this dissertation employs heart rate and brainwaves as physiological signals to assess the entrainment of humans. There are many occasions that need entrainment, such as group learning on educational occasions and group work on work occasions; these occasions need intermediaries for realizing smooth collaboration, such as a teaching assistant, a moderator, and a coordinator. However, intermediaries are difficult to find in many cases because of the shortage of human resources. Therefore, this dissertation proposes entrainment promoting robots as assistants to improve human-human interaction and increase their cooperative performance.

This dissertation proposes to utilize robots to assist the corporation among humans. The proposed "entrainment promoting robot" promotes interpersonal entrainment and assists cooperation and smooth communication among humans by participating as an intermediary. The dissertation has three contributions; first, it is confirmed that the heart rate and brainwaves have the same entrainment phenomenon; second, it is confirmed that a robot can affects the internal state of humans through communication with expressions and dialogue; third, an assessment method of physiological signal entrainment considering a delay in physiological signal is proposed.

First, an experiment is conducted to investigate the relation of entrainment between heart rate and brainwave. In the experimental condition, the experimenter imitates the subject's actions, articulation, and voice volume when talking about a common interesting topic. On

the other hand, in the control condition, the experimenter behaves opposite to the subject's actions, articulation, and voice volume. Their heart rate and brainwave are collected during the experiments and analyzed by Pearson Correlation Coefficient (PCC) as the assessment method. The results show the delay of the physiological signal entrainment from heart rate (LF/HF ratio) to brainwave (Beta/Alpha ratio) is around 40-60 seconds, and the brainwave response speed is faster and more sensitive than the heart rate. However, there is no significant difference between the result with imitation behavior and that in the control condition, which implies simply imitating a partner is not enough for promoting entrainment.

Based on the result of the first experiment, the second experiment is conducted to verify whether a robot affects the internal state of a human through the robot's movement and expressions. In this experiment, subjects wear a heart rate sensor and a brainwave sensor, and asked to answer true or false to math questions given by the robot. After the subject answers the questions, the robot expresses happiness or worried behavior according to whether their answer is right or wrong. A worried expression is used to give a proper pressure so that they can think questions seriously. The results show the robot affects the internal state of a human through its movement and expressions.

Finally, the entrainment promoting robot that encourages interpersonal entrainment through dialogue is developed. This dissertation also proposes an assessment method of entrainment that employs Dynamic Time Warping (DTW) and PCC to analyze Power Spectral Density (PSD) data from heart rate and brainwaves. This experiment was conducted with two subjects in each experimental group. One subject holds a clue and the other fills a grid of a crossword respectively, and they communicate and cooperate to complete the crossword in a limited time. In the experimental condition, the robot tells the subjects the time with different dialogues and expressions of anxiety. The control condition is conducted without the robot. The experimental results show that the average completion rate of tasks was 92% with the robot and 82% without the robot, respectively. It was also observed the subject tended to talk more frequently in the experiment with the robot than in the control condition, which indicates using the robot as an intermediator is helpful for human communication and for improving the performance of cooperation. In terms of the entrainment assessment, DTW is found to be more suitable than PCC. It was also confirmed that different from regular synchronization that is the phenomenon observed at the same time, the physiological entrainment between humans observed in the experiment had a “time delay”: the entrainment of partners (collaborators) was observed in the same time segment, but not at the same time. This finding is expected to be examined by subsequent studies in the future.

The dissertation is composed of 6 chapters. Chapter 1 introduces the background and motivation. Chapter 2 describes the concept of entrainment promoting robots and the entrainment assessment method. The experiment for investigating the relation of entrainment between heart rate and brainwave is described in Chapter 3. The second experiment to confirm the effectiveness of a robot for affecting the internal state of a human is described in Chapter 4. The third experiment using the entrainment promoting robot and the result of assessing the entrainment are described in Chapter 5. Chapter 6 presents the conclusion and discusses the future direction of the research based on the findings of the dissertation.

Contents

Chapter 1

Introduction

1.1 Background

Recently, technology has advanced significantly to cater to the diverse needs of human beings, bringing comfort to our lives. Human beings are always trying to innovate new technologies to enhance comfort, leading to a rapid increase in robotic development. With robots increasingly taking over human labor and basic operations, developers are trying to create technological products that can save on human resources spent on daily activities or other repetitive processes and even help humans in another way, e.g., using robots as supporters to help humans, which is a way to decrease human resources cost in disguise. This background support human-robot interaction and human-robot cooperation research becoming a deep and enthusiastic topic in robotics research.

There are already many studies on human-robot cooperatives. For example, the research presented that during human-robot cooperation when robots' human-likeness matched the sociability required in human jobs, people preferred robots [1]. The other research proposed an architecture for the proactive execution of robot tasks in the context of human-robot cooperation with uncertain knowledge of the human's intentions [2], this research indicates human intention or human internal condition is essential for human-robot cooperation, that's why this dissertation focuses on entrainment which is one of the expressions of internal condition. The purpose of this dissertation is to propose a robot to promote the entrainment between humans in cooperative occasions that need communication and cooperation includes educational, work, and so on.

Human-robot interaction (HRI) is roughly divided into four applications, human supervisory control of robots in routine tasks, remote control of robots, automated vehicles, and human-robot social interaction [3]. Regarding work occasions, the robot is usually applied on "human supervisory control of robots in routine tasks" [4] [5]. In the part which focused on "human-robot social interaction", e.g., rehabilitation and assistance in the elderly and handicapped in hospital [6], situate social robots in public spaces and enhance customer experience [7].

Regarding education occasions, robotic utilization is more focused on "human-robot social interaction," and robots improve students learning performance in numerous ways compared to traditional teaching methodology without robots. For example, Kanda's team applied for an elementary school's English class for two weeks. The robot interacted with students by speaking English, and it affected improving their English ability. The study showed a positive correlation between the frequencies of interacting with the robot and learning performance [8] [9]. Wichita County, Western Kansas, uses Robot Roadshow to increase the interest of elementary students in science, math, and other technical areas [10]. The program includes pre-visit activities to help the students obtain the basic knowledge of robots, followed by a multimedia presentation that provides hands-on experiments with real robots. It was extremely popular with students and teachers, with more than 1,200 children participating in the program. Lee et al. used AI-FML (Fuzzy Markup Language) [11] [12] robotic agent for student learning behavior ontology construction, which applied in the English speaking and listening domain and introduced it as a human and machine co-learning class to the Rende elementary school in Taiwan in 2019 and 2020 [13].

The mentioned above prove the possibility of robot development in various fields, the literature further divides educational robot into several types and analyze the robot's problem and application [14].

In term of applying robots to interpersonal collaboration, there is a lot of research. MF Jung et al. (2015) use robots as an emotion regulator to benefit human collaboration [15]. B Mutlu et al. (2009) designed gaze behaviors for a robot to cue three kinds of participant roles: addressee, bystander, and overhearer to participate in interpersonal communication [16]. D Rifinski et al. (2015) discovered the robot's responsive gestures contributed to participants' positive direct interpersonal evaluation [17]. S Strohkorb et al. (2016) presents via using the robot to ask question among humans can improve performance measures and perception of performance in groups [18]. This dissertation also focuses on applying robots to improve interpersonal collaboration, but the difference is that this dissertation approaches from the viewpoint of entrainment promotion. In this dissertation, robots' "expressions" and "dialogues" are used to promote interpersonal entrainment that is verified, then improve communication among humans and the human performance at "group learning/work."

1.2 Motivation

Society is like a large machine, human beings are like gears. Just as lubricating oil smooths many gears in the machine, good "communication" and "cooperation" smooth society like lubricating oil. "Entrainment" is a kind of lubricating oil in human-human interaction, it is essential for good communication whatever type of entrainment such as acoustic and prosodic [19], behavior entrainment [20], and heart rate entrainment [21] etc.

There are many occasions that could be used robotic assistance to improve human communication, as a case in point, from group work at elementary school to workshops at college, there are many kinds of patterns for cooperative work in educational occasions. On work occasions, there are many meetings to be held in companies, if we could via the entrainment promoting robot to improve their communication and increase their cooperative performance. The novel robot application mentioned in Section 1.1, which provides benefits for various occasions which need cooperation. The occasions mentioned need intermediaries to smooth, such as a teacher, conductor, etc., my proposed robot application can be replaceable. Therefore, this research proposes an "entrainment promoting robot" which promotes interpersonal entrainment and assists cooperation among humans, which smooths communication by participating as an intermediary.

Regarding work occasions, there are many researchers studied about importance of "communication" and "group work" in organizations, e.g., Radovic Markovic et al. (2018) wrote "Communication, as a management function is a process of creating, communicating and interpreting ideas, facts, opinions and feelings about work performance, organizational effectiveness and efficiency as well as goals attainment in an organization" [22], Zwijze-Koning and de Jong (2005, p. 429) highlighted that, "The importance of communication for the effectiveness of organizations and the wellbeing and motivation of employees is undisputed" [23]. In addition, research has shown how harmful or dysfunctional leadership communication can be disastrous for business organisations [24] [25]. Regarding education occasions, Edmondson (1999) defined the definitions of group learning as "An ongoing process of reflection and action, characterized by asking questions, seeking feedback, experimenting, reflecting on results, and discussing errors or unexpected outcomes of actions" [26]. In addition, scientists and engineers work mostly in groups and less often as isolated investigators.

Therefore, students should gain experience sharing responsibility for learning and cooperative work with each other since childhood [27]. In group learning/work, the human learned how to share their thoughts, receive different opinions from each other, etc., which benefit cooperative work, that is why group learning/work is important that applied from elementary school to college and even organizations/company in every country, and the purpose of this dissertation is use robot to improve performance of group learning/work.

My research motivation is that robots are expected to become assistants to support humans to improve cooperative performance on educational occasions, work occasions, and other occasions, work occasions, and other occasions. Different from the related works mentioned in Section 1.1, this dissertation focused on applying robots to improve "group learning" and "cooperative work", the teacher or team leader organizes the whole task, and the robot participant in the group learning/work as an intermediary, as shown in Fig. 1.1. To achieve this goal, this dissertation is constructed of three main parts. 1) the first part presents the human state detected based on physiological signals and the assessment method of physiological entrainment. 2) To ensure brainwaves have the same entrainment phenomenon as heart rate and the Robot (Kebbi) affects the internal state of humans through its expressions and movement. 3) Finally, apply robots in human-human interaction as assistants to improve their communication through promoting entrainment between humans and observe the impact of entrainment promoting robot participation.

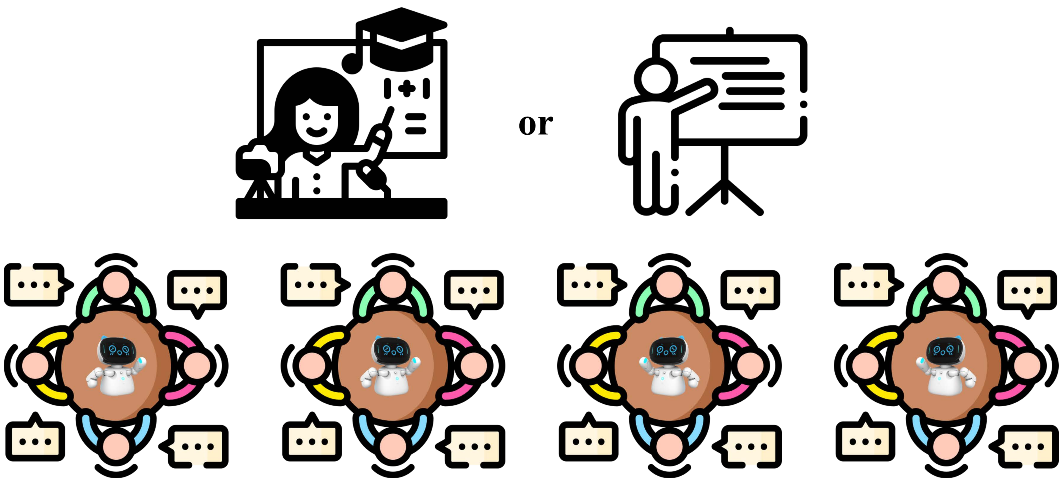


Figure 1.1: Hypothetical Application of Robots as an Intermediary

1.3 Organization of Chapters

This dissertation focuses on developing an entrainment promoting robot that smooths communication between humans, therefore the chapters are split into three parts, "Entrainment", "Analysis of Relation between Brainwave and Heart Rate Information towards Entrainment Robot Assistance" and "Observation of Human Entrainment with Robot Assistance". Firstly, it is significant whether the entrainment phenomenon occurs between humans, and how to observe the entrainment phenomenon with physiological signals. In order to observe the entrainment phenomenon state between humans, this dissertation used brainwave sensors and heart rate sensors as physiological signal sensors. Section 2.3 and Section 2.4 introduced the relevant knowledge, information, and assessment method for observing the phenomenon. Secondly, in Chapter 3, I observed the relationship between brainwave and heart rate entrainment by using the assessment introduced in Section 2.4 to confirm brainwaves have the same entrainment phenomenon as the heart rate. In Chapter 4, considering different expressions of robots that affect humans with different effects, there is an experiment that recorded the differences in human reactions. Finally, in Chapter 5, after confirming the two phenomena which need to verify, I applied robots to human cooperative work and analyzed human physiological signals and cooperative performance.

This dissertation comprises chapters six chapters. The chapters' position is depicted in Fig. 1.2. The specific description of each chapter is described as follows.

Chapter 1: This chapter introduces the background, motivation, and overall structure of this dissertation.

Chapter 2: This chapter describes the definition of entrainment in this dissertation and defines the difference between entrainment and synchronization. Conventional research about entrainment deals with human acoustic and prosodic motion while this dissertation focuses on physiological signal entrainment. Section 2.1 introduces the entrainment phenomenon between humans regarding conventional research. Section 2.2 introduces the human-robot entrainment regarding conventional research. Section 2.3 explains the physiological signals, brain signals, and heart rate signals, which are used in this dissertation with used sensors and analyzing features. Brain-Computer Interface (BCI) and Heart Rate Monitor (HRM) are introduced in Section 2.3.1 and Section 2.3.2 respectively, and the employed features are introduced in Section 2.3.1 and Section 2.3.2. Section 2.4 explains two entrainment assessments used in this dissertation, one is Pearson Correlation Coefficient (PCC), and the other one is Dynamic Time Warping (DTW). The reason for choosing, related work, and the method of PCC and DTW are explained in Section 2.4.1 and Section 2.4.2 respectively. Section 2.4.3 discusses the comparison in PCC and DTW.

Chapter 3: This chapter presents the analysis of heart rate and brainwave entrainment through imitating features of conversation. Section 3.1 introduces why brainwaves and heart rate were chosen, and the research about the effect of imitation in interpersonal interaction. Section 3.2 describes the experiment design, including the sensors used, the experiment environment, the schematic of the experiment, and the analysis method. Section 3.3 describes the analysis of the experimental results, from the viewpoint "Entrainment through Imitation" and "Relationship between Heart rate and Brainwaves Entrainment". "Entrainment through Imitation" compares the impact of imitation and differentiation. "Relationship between Heart rate and Brainwaves Entrainment" observes the difference in the entrainment phenomenon of Heart rate or Brainwaves. Section 3.4 discusses the relation between heart rate and brainwaves in entrainment and the conclusion of using imitation to improve entrainment occurs.

Chapter 4: This chapter presents whether a robot can affects the human internal state with expressions and motion, the expressions and motion employed, and the effect they bring. Section 4.1 introduces the reason for choosing the humanoid robot, Kebbi, for this experiment. Moreover, the specification of Kebbi, and its expressions used in this experiment are described. Section 4.2 explains the reason for only using two kinds of expressions and the design approach of the quiz used. Section 4.3 describes the whole experiment design, including the experiment procedure, the subject's age, gender, etc. Section 4.4 discusses the experiment results and analysis results. Section 4.5 discusses the conclusion of applying Kebbi to affect the human internal state.

Chapter 5: This chapter presents applying Kebbi which participates in human-human interaction (HHI) as an intermediate. Observing the effectiveness of using a robot in an HHI situation (based on the number of times of entrainment and completion rate). Section 5.2 describes the experiment design, including participants' age and native language, cooperative task, schematic of the experiment, expression, and dialogue of Kebbi. Section 5.3 describes experiment results, including entrainment times dialogue times, and completion of the task in each group. Section 5.4 describes our conclusion and future work on this chapter.

Chapter 6: This chapter describes the conclusion and effectiveness of the experimental results of each chapter, followed by the potential application and prospects of further development.

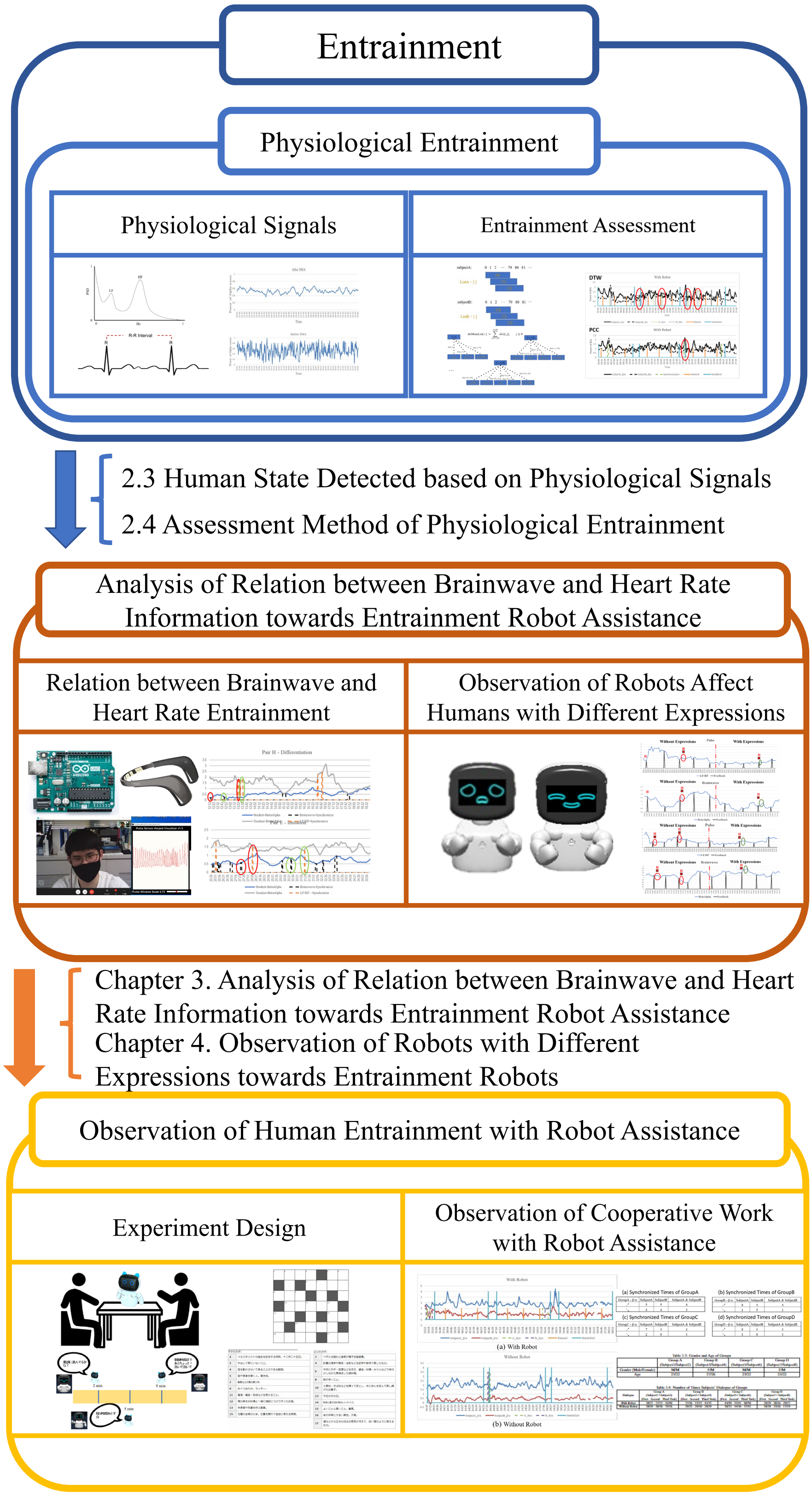


Figure 1.2: The illustration chapters' position

Chapter 2

Entrainment Promoting Robot

Eric L. Bittman writes that "it is often stated in lectures, textbooks, and even refereed scientific publications that entrainment is equivalent to synchronization, which is inaccurate and misleading" [28]. The definition of "entrainment" and "synchronization" is unclear in may publications. In this dissertation, I define as follows, the events that happened with the same variation at the same time, are explained as they have "Synchronization". A similar phenomenon is that the experimental events with the same variation but which may delay or occur at the same time, are explained as they have "Entrainment". There fore, "Synchronization" phenomenon is included in the "Entrainment" phenomenon. In this dissertation, I propose a new application "Entrainment Promoting Robot", which use robot as an intermediate to improve the entrainment phenomenon among humans. The robot reminds the time with different dialogues and expressions to show varying degrees of anxiety to promote subjects occur entrainment, the actual application refers to Chapter 5.

2.1 Entrainment between Humans

The purpose of focusing on entrainment phenomenon in this dissertation is to promote communication between humans. General human communication is through verbal communication to an exchange of information between people, human speech perception is accomplished by coupling the ongoing rhythmic neural activity of the listener and the quasi-rhythms of the speech signal [29] - [31]. In addition to speech, human communication also includes many factors, such as facial expressions, internal state, body movements, etc. Therefore, the entrainment phenomenon is naturally related to these elements. The entrainment phenomenon includes various types, it across gender, age, language, and race, it occurs between humans in many appearances, such as body movements entrainment with sounds, speech entrainment, even between heart rate, and between brainwaves, among others. The universal nature of human entrainment is also supported.

This paragraph reviews various types of entrainment with traditional studies. Condon et al. (1974) [32], the time-motion analyzer is used to analyze each image frame; the detected parts include eyebrows, eyes, and mouth. In addition, they used frame-numbered sound films of the oscilloscope display of the speech to ensure accuracy in locating speech segment boundaries in relation to the frame numbers. They discovered that human neonate moves in precise and sustained segments of movement that are synchronous with the articulated structure of adult speech. As a person speaks, multiple parts of the body move in different directions and at different paces, and yet at brief periods, these seemingly random movements may relate to each other at 0.04 to 0.16 seconds. This shows that no matter how random these movements may seem, there ultimately exists minuscule similarities between such movements in different people when they are speaking. It supposes that the entrainment phenomenon between people is possible. Adam Kendo [33]— whose studies are the source of most of the examples to be analyzed—used an eighty-minute 16 mm black and white sound film of a gathering in the private lounge of a middle-class London hotel, and he discovered the correlation between body movement and speech communication. Another study discovered people's unconscious imitation behaviors to close people with who they like in conversation. Such behavior is a kind of entrainment. When people are in conversation, they adapt their speaking style to their conversational partner in a number of ways [34]. Besides entrainment mentioned above, an influential paper [35], observed that during the interaction between humans, compared to the same words spoken before the interaction, the words spoken of them become more similar in their phonetic and prosodic characteristics.

In terms of physiological entrainment, based on the previously known fact that variation of heart rate and brainwaves has been used as an indicator of the internal state which will be explained in Section 2.3. The paper [36] analyzed face-to-face interaction on the basis of heart rate and its variability as indices. They observed the indices in both mother-infant interaction and adult conversation have synchronized time changes. It suggests the entrainment in nonverbal interaction is biologically necessary for human communication. Gomi et al. (2019) discovered the entrainment phenomenon of pules in an experiment involving a conversation on video chat [37], soon after, my study also evidences to suggest that brainwaves and heart rate exist in a similar entrainment phenomenon [38].

This dissertation focuses on researching physiological entrainment. Movements and speeches used to observe entrainment in conventional research are controllable by him/herself. Hence, I employ heart rate and brainwaves as physiological signals to assess the entrainment state of humans in this dissertation.

2.2 Human-Robot Entrainment

Before talking about the entrainment of human-robot, we discuss the human-robot interaction first. HRI is a rapidly developing field and a multi-disciplinary approach with contributions from many fields, including robotics, cognitive science, human factors, natural language, psychology, and human-computer interaction [39]. In this dissertation, the most relative is psychology and human-computer interaction. The occurrence of entrainment is affected by human interaction and human psychology. There are many researchers who studied on human-robot entrainment. Literature written by Cynthia Breazeal (2002) presents that naive human subjects interact with an anthropomorphic robot, evidences for mutual regulation and entrainment of the interaction, and discuss how benefits of interaction. This study through the features of prosodic to recognize the affective intent of humans, e.g., maximum energy, energy variance, energy range, pitch variance, energy variance, and pitch mean. On the other hand, in the robot development study, continual small adjustments in body posture, gaze direction, head pose, and facial expression serve to synchronize the movements of a robot and a human. This experiment shows that bringing the robot and the human into a state of affective synchrony [40]. Iio et al. (2009) discovered that lexical entrainment exists in human-robot interaction [41]. Ansermin et al. (2017) show that study rhythmical interactions during imitation games between NAO and naive subjects [42]. Furthermore, Molenaar B et al. already studied about applying human-robot entrainment in education [43]. The difference between the study to this dissertation is that tried to use speech entrainment to improve language learning, but this dissertation used physiological entrainment to improve interpersonal collaboration. Robots have never physiological signals, therefore, robots are used as an intermediate to improve entrainment, instead of directly human-robot interaction in this dissertation.

2.3 Human State Detected based on physiological signal

This section describes the approach to assessing the human state is detected by physiological signal sensors. There are two approaches, PCC and DTW, used in this dissertation are described in Section 2.3.1 and Section 2.3.2 respectively. Different from the previous studies, considering this application could be applied to the scene easily, this dissertation used a handy sensor to analyze. Section 2.3.1 describes a method which assessed the human state by brainwave, β/α ratio. Section 2.3.2 describes a method that assessed the human state by LF/HF ratio from heart rate variability (HRV).

Human communication includes many things besides verbal interaction, there are nonverbal interactions, internal states, etc. This section introduces the signals used to understand the human internal state and describes two kinds of physiological signals, HRV, and brain waves. Compare to the other physiological signals (temperature, galvanic skin response (GSR), respiration (RSP), etc.), the reaction speed of brainwaves and HRV is able to provide that lets the robot conduct real-time feedback to be passable, and the signals include more meaning which analyzable. The relative studies are introduced in the following sections, which features of the signals are used as the evaluation basis, and the method of processing the data. The devices, to obtain the physiological signal characteristics and the reasons for choosing them are also introduced.

2.3.1 Brainwaves

Brain-Computer Interface (BCI)

Brain-Computer Interface (BCI) [44] is the communication pathway between the brain's electrical activity and external devices. BCI is roughly divided into invasive, partially invasive, and non-invasive types. This dissertation used non-invasive electroencephalogram (EEG)-based BCI. EEG is a method that records an electrogram of the electrical activity on the scalp. It has been proved that it represents the macroscopic activity of the surface layer of the brain underneath the scalp. Hans Berger first discovered EEG in 1924; he recorded human brainwaves and improved upon them in the future years following the discovery [45]. The discovery is an integral part of BCI, which is used in many experiments and real-life applications. The early application of BCI had applied to alternative interfaces for severe motor disturbance persons. They conducted some simple operations through brain waves without any muscle control through systems based on the P300 component of the event-related brain potential (ERP) [46], for example, L.A. Farwell and E. Donchin (1988) developed a system that is able to let severe motor deficits communicate through a computer [47]. Jonathan R. Wolpaw et al. (1991) [48] made a system to use the 8-12 Hz mu rhythm recorded from the scalp to move a cursor. In recent years, many studies have been directed towards using BCI to observe human internal state such as Mental State Recognition via Wearable EEG [49], Detection of Driver Vigilance Levels Using EEG Signals, and Driving Contexts [50].

The concept of this dissertation attempt to apply to various occasions which need communication directly. Therefore, a dry electrode-type brainwave sensor is employed to ensure that users do not need to smear on ecotrode gel. Muse [51], which is used in this dissertation, is a simple BCI device developed by the Massachusetts Institute of Technology, IBM, NASA, the University of Toronto, and Yale University with four possible electrode positions. In comparison to previous models, this device has fewer electrode positions. However, this BCI device uses dry electrodes (Fig. 2.1). Muse monitors α, β, θ, δ, and γ brainwaves, by four channels, which is corresponding AF7, AF8, TP9, and TP10, shown as Power Spectral Density (PSD) [52] with a reference electrode as FpZ (Fig. 2.2).

Figure 2.1: Muse Sensor

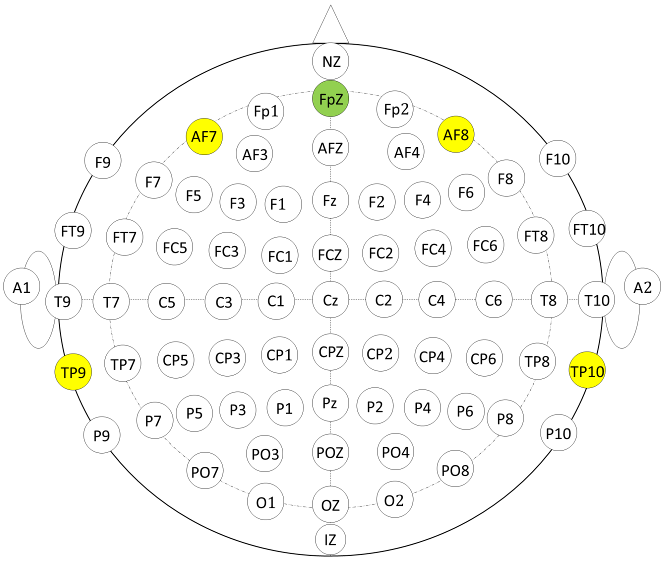


Figure 2.2: Channels of EEG Sensor (Muse)

β/α **Ratio**

There are many ways to analyze brainwaves, e.g., using a phase synchrony measure known as phase locking value (PLV) [53], but in this dissertation, I want to compare with the heart rate, therefore I chose to use a similar method to analyze which using PSD.

Brainwaves are roughly divided into five different waves, α, β, θ, δ and γ bands. The δ and θ bands belong to lower frequency and usually occur when people sleep or are half-asleep and half-awake. Then α and β are split into low, medium, and high regions. The middle α band and low β band appear when the subject is concentrated yet in a relaxed state of mind. The Middle β band is associated with the thought and sorting of data. Research shows that the β band is connected to the awareness level of the subject, while the α band primarily appears when the subject is relaxed. The subject appears to be interested in the topic, β and α waves usually fluctuate, therefore some experiments use the β/α ratio to recognize emotion [54] - [58].

For example, Liu et al. (2018) processed the β/α ratio detected from the frontal lobe by a Support Vector Machine (SVM) classifier to recognize emotions. This paper also mentions that the α wave is related to relaxation level and the β wave is related to concentration level [59]. In the other papers, the results show that there are fluctuations of α and β waves when athletes are very focused [60] - [62]. Tee Yi Wen et al. (2020) used a VR video of a suitable fearful and stressful scene as stress elicitation to analyze the activity of brainwaves; the results showed that α/β ratio and θ/β ratio is negatively correlated with stress [63]. Relaxation and concentration are an indicator of the state of cooperative work. Similar to the papers mentioned above, I decided to observe the entrainment of the β/α ratio as an indicator to assess the state of cooperative work of subjects in this dissertation.

2.3.2 Heart Rate

Heart Rate Monitor (HRM)

Heart Rate Monitor (HRM) [64] [65] is a monitoring device that measures heart rate and records it in real time. Most research uses two types of sensors, the first, which measures the bio-potential generated by electrical signals called Electrocardiography (ECG) [66] [67], and the second which uses light-based technology to measure the blood controlled by the heart's pumping action called Photoplethysmography (PPG) [68] [69]. ECG is an important part of HRM, which is applied in many experiments such as Aizawa et al. (2017) analyzed the heart rate while humans communicate with a chat robot via video chat [70] and Gomi et al. (2019) analyzed the heart rate of humans when they are video chat [37] and so on. In this dissertation, the Arduino [71] HRM is chosen in experiments 2.3.

Figure 2.3: Arduino Heart Rate Monitor (HRM)

Heart Rate Variability (HRV)

HRV analysis in the frequency domain requires a Holter system [72] [73] with a calibrated timing signal. Frequency domain analysis produces information about the variance in the rhythm of the heart which is explained by periodic oscillations of heart rate at various frequencies. These frequencies, when grouped together in bands, provide a method to understand the cardiac autonomic modulation, and the standard approach which calculates power in four bands is introduced in the paper [74].

R-R interval [75] [76] indicates the change between heart rate peak (R wave) occurrence time and the next R wave occurrence time. I calculated the time series data of R-R interval fluctuation, and then obtain power spectral density by performing spectrum analysis it. Low-frequency (LF) power is a power spectrum in the frequency band 0.004 to 0.15 Hz and reflects the tension of both sympathetic blood pressure and parasympathetic. The effects of parasympathetic appear in the LF while taking deep breaths with a respiratory rate of 9 or less per minute. When breathing slowly and regularly in a relaxed state, the LF value is very high, which means parasympathetic are increasing. High-frequency (HF) power is a power spectrum in the frequency band 0.15 to 0.4 Hz and reflects the tension of parasympathetic in respiratory variability. Heart rate increases when you inhale and decreases when you exhale. Slow and regular breathing increases the HF value [77] [78]. There is a consensus that, under normal circumstances, HF power reflects vagal modulation of the heart rate [79], it has been claimed that LF—especially normalized LF power, which is LF/LF+HF—reflects primarily sympathetic modulation of heart rate [80], and that the LF/HF ratio reflects "sympathovagal balance" [81]. This dissertation used the LF/HF ratio required by frequency analysis of R-R interval (HRV) as the vital sign, observed the time series data of LF/HF ratio fluctuation, and analyzed it.

There are many researchers who study about through power spectral to understand the human internal state, e.g., Nancee V. Sneed et al. (2001) used the steps developed by Krieger and Kunz called therapeutic touch (TT) [82] for an experiment to analyze the power spectral of heart rate variability and the influences of a relaxation intervention on perceived stress [83]. F Shimono et al. (1997) adopt the ratio of LF and HF using sympathetic stress rating [84], stress evaluation when listening to unpleasant sounds [85], determining whether there is a tendency to depression [86], etc. LF/HF represents the overall balance of sympathetic and parasympathetic. A high value indicates sympathetic dominance, and a low value indicates parasympathetic dominance. LF/HF is also considered to exist in different stress states depending on the length of time used for analysis [87]. In the current research, it is prevailing to calculate LF/HF in real time considering [88], and it is possible to make the conversation support robot grasp the interlocutor's mental state. It is necessary to reduce as much movement as possible when measuring heart rate with pulses from the fingers or the ear, it may be affected by the stability of contact with the measuring instrument.

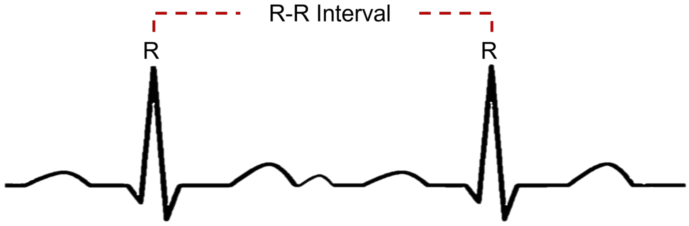


Figure 2.4: R-R intervals (HRV)

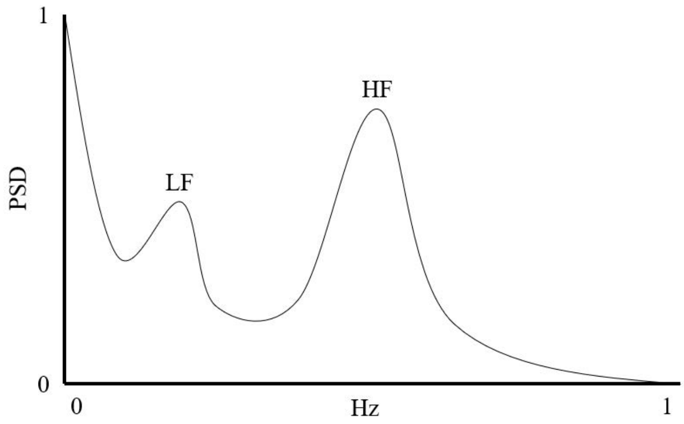


Figure 2.5: LF component and HF component

2.3.3 Simple Moving Average (SMA)

Simple Moving Average (SMA) [89] is the mean taken from an equal number of data on either side of a central value. It is a method often used in removing noise from original data (Fig. 2.6) to convert it to data that be understood easily (Fig. 2.7). In this dissertation, I use 25 seconds as shift time to process the data collected; the shift time follows the paper which compares the synchronization phenomenon between pulses and brainwaves [38]. It is defined as eq. (2.1)

$$x = \frac{\sum_{k=1}^{n} X_K}{\text{n}} \tag{2.1}$$

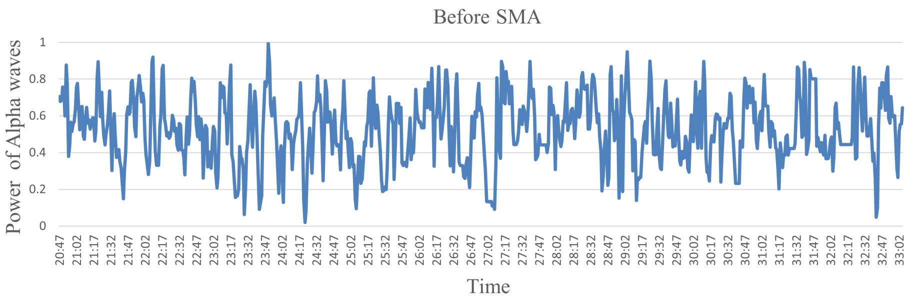


Figure 2.6: Before Rolling Average

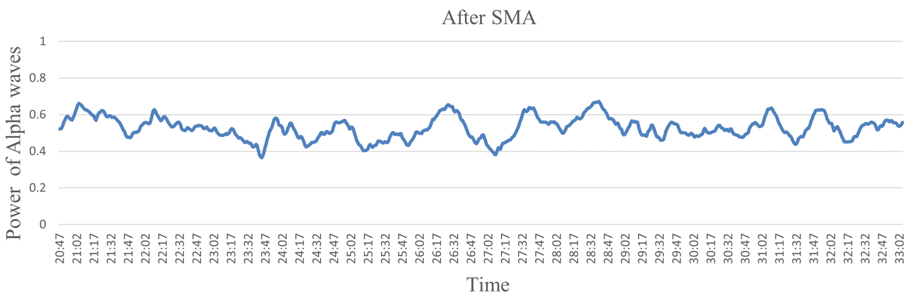


Figure 2.7: After Rolling Average

2.4 Physiological Entrainment Assessment

In the preprocessing, fast Fourier transform (FFT) [90] is the method that increased the effectiveness of digital methods, it has been used to solve problems such as signal processing, spectral analysis, Fourier spectroscopy, image processing, and the solution of differential equations [91]. In this dissertation, after using FFT to transform data to power spectral density (PSD), I chose two kinds of algorithms to analyze data of PSD, Pearson correlation coefficient (PCC) [92] and dynamic time warping (DTW) as an assessment to assess entrainment, which will be explained in this section.

2.4.1 Pearson Correlation Coefficient (PCC)

PCC is used to calculate the linearity correlation between two data sets. The calculated result is usually between -1 and 1. The literature evaluated various time-history data curves by PCC [93], the data sets evaluated were the simple model, bimodal/force model, real data model, running VGRF data, drop landing VGRF data, and hybrid data model. The result shows PCC is easy to use and be used to evaluate the entire curve as opposed to discrete data points, this algorithm is suitable to analyze data sets of PSD.

Yang Shi and Fangyu Li et al. (2018) used wavelet packet decomposition (WPD) [94] and the DTW extracted features detected from Electroencephalogram (EEG) [95], the study demonstrates the way of using temporal sequence similarity measurement in time series data analysis. Referring to the study, 80 seconds as the window is used to process brainwaves, but the result showed there are not any entrainment phenomena that occurred in the experiment data analyzed by PCC, half of 80 seconds, 40 seconds as the window used lastly shown in Fig. 2.8. If the result of similarity is above 0.9 and continues to occur in three seconds, the part as the entrainment phenomenon is assessed that occurred.

2.4.2 Dynamic Time Warping (DTW)

Dynamic time warping (DTW) [96] is an algorithm for measuring the similarity between two temporal sequences. However, the two periods that need to be compared may not be of the same length. For example, in the same sentence, some people will speak very rapidly while others will speak very slowly. Even if the same person speaks at different rates, the

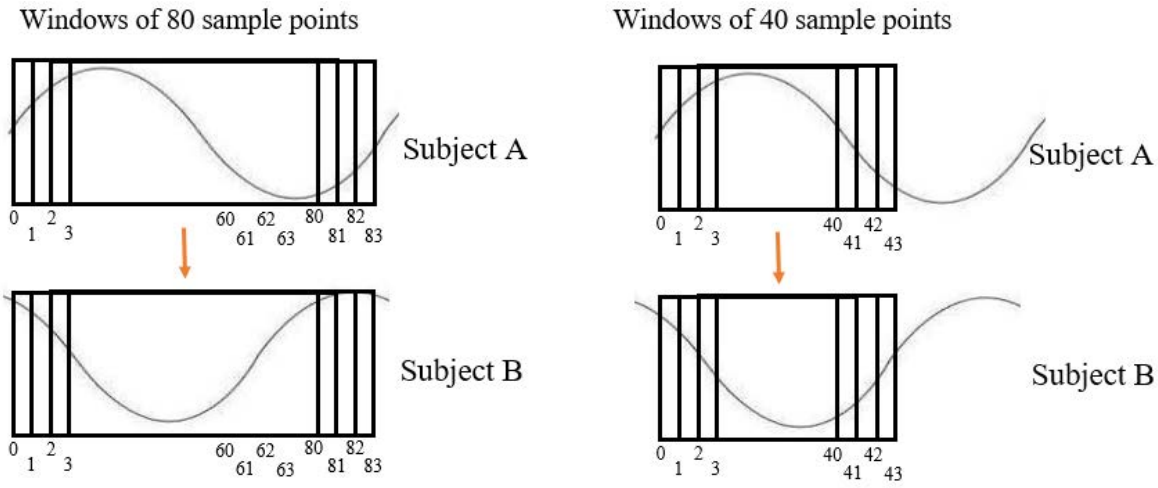


Figure 2.8: Entrainment assessment by using PCC (window sizes)

pace of speech cannot be the same. In these complex cases, the distance (or similarity) between two-time series cannot be efficiently obtained using traditional Euclidean distance. DTW calculates the similarity between two-time series by extending and shortening the time series. After warping a sequence, it can be recovered by overlapping with another sequence [97]. In the same segment of the "entrainment" phenomenon, whose brainwaves have been entrained first are uncertain. To resolve this uncertainty, I approached this project using the FastDTW algorithm [98], a linear and accurate approximation of DTW that can run larger data sets to analyze brain activity, than traditional DTWs [99]. To find the similarities between brainwaves, two subjects, A and B, are randomly selected. Subject A is the base reference for the comparison. A sequence of numbers over a period of 80 seconds makes up a window, and each number within each second will be an average of 250 sample points. Subject A has windows starting at the 30-second mark, with a window for every second. It is compared to subject B's windows, starting 30 seconds before and after the initial point of time, i.e., if the initial point of time for subject A is at 30 seconds, then the sequence of numbers between the 30th sec. and 110th sec. (80 sec. difference) will be one window, and this window will be compared to all the windows for 0-60th sec. to 80th-140th sec. of subject B. There will be 60 comparisons for each window of each subject. The comparisons will continue with the 31st sec. A window of subject A will be compared to the 1st-61th sec. windows of subject B, and so on, as shown in Fig. 2.9. All distances (similarity) are calculated before and after 30 seconds frames, adopt an average and add it to the List, if the distance is less and equal to 0.01 quantile of the “disMeanList”, then an entrainment phenomenon is identified as shown in Fig. 2.10.

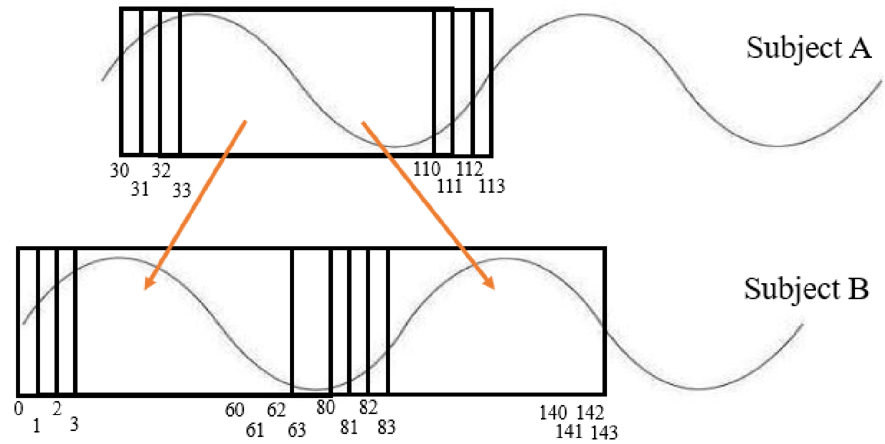


Figure 2.9: Entrainment assessment by using DTW (window sizes)

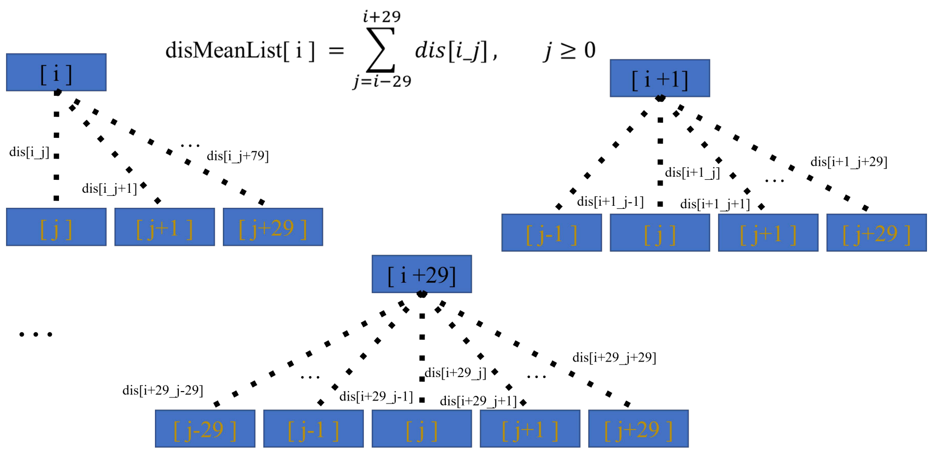


Figure 2.10: Algorithm of DTW on Entrainment Assessment

2.4.3 Comparison in Entrainment Assessment

The experiment design and experiment data detected are introduced in detail in Chapter 5. The average of 30 seconds before and after a reminder are calculated, each reminder as a set to observe the fluctuation of them as shown in Table 2.1. The times above each row are the increased times of the group, and the times below each row are the decreased times of the group. The first column is times of increase and decrease of subjects who hold the answer sheet, the second column is times of increase and decrease of subjects who hold the question sheet, and the third column is times of both "increase" or "decrease" simultaneously. On the other hand, I compared the result calculated by different from two types of algorithms as shown in Fig. 2.11, above one is the result calculated by DTW, and below one is the result calculated by PCC. The black line is the β/α ratio of the foreigner who holds an answer sheet, the black dot line is the β/α ratio of the Japanese who holds a question sheet, the orange line is the timestamp of reminders, and the blue line is start and end of each task. According to algorithms, the entrainment of DTW is divided into two colors of dot lines, the green dot line is the entrainment of foreigners, and the purple dot line is the entrainment of Japanese. The entrainment of PCC only has the green dot line as part of the entrainment. The entrainment is expected to occur after the timing of start, end, and before & after the reminder, then the number of times the parts which match my expectations are counted. As shown, the red circle are the parts that matched my expectations, and the matched parts which recognized matching with DTW are more than PCC.

Table 2.1: Brainwave fluctuation times of before and after the reminds each group

	Subject Answer Sheet	Subject Question Sheet	Simultaneous occurrence both subjects
Group A	5	5	4
	4	4	3
Group B	8	4	4
	1	5	1
Group C	7	3	2
	2	6	1
Group D	8	3	3
	1	6	1

2.5 Summary

The hypothesis is physiological signals may have the same entrainment situation with movement, acoustic, prosodic, etc. mentioned above that in entrainment, the variation of humans may have sequential order, which means one will change with the other. Therefore, the DTW and PCC are used in the comparison.

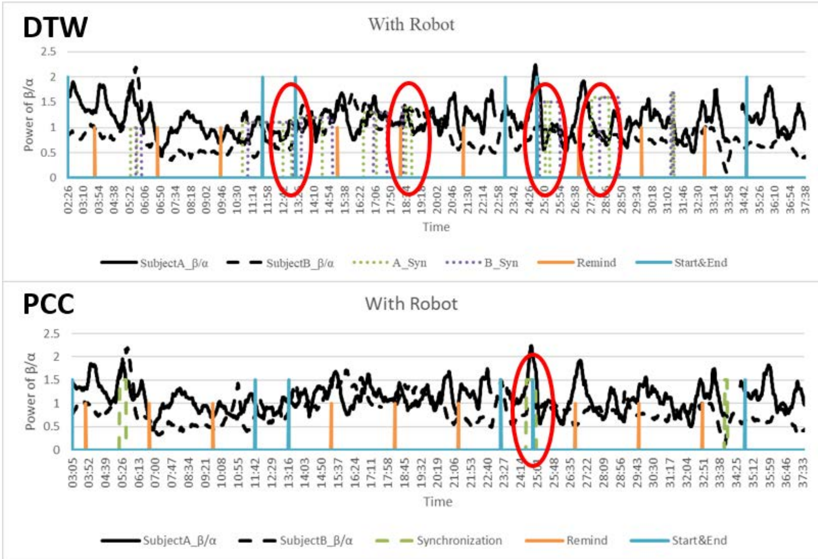


Figure 2.11: Result of DTW and PCC

The goal of this dissertation is to use robots to improve the frequency of entrainment phenomenon between humans to enhance the communication efficiency and cooperative performance of humans. To achieve this goal, I have three research topics. Firstly, since Aizawa et al. (2017) discovered the entrainment phenomenon analyzed by PSD of HRV [70], an experiment is designed to confirm there is the same entrainment phenomenon between brainwaves and heart rate, which is introduced in Chapter 3. Secondly, the experiment is designed to confirm the robot (Kebbi) affects the internal state of humans, it will be introduced in Chapter 4. Thirdly, the experiment is designed to confirm the robot participating in human-human interaction as an intermediate improves the entrainment phenomena between humans, it will be introduced in Chapter 5.

In future work, I would like to let robots be along with human states to do the different reactions in real-time. Therefore, there is an important thing during human interaction in this study, the state of humans needs to obtain as soon as possible, then the reaction of robots be changed faster. Compared to heart rate, brainwaves' reaction speeds are faster and more sensitive to the entrainment phenomenon which reaches the requirements [100].

Chapter 3

Analysis of Relation between Brainwave and Heart Rate Information towards Entrainment Robot Assistance

This experiment is conducted to investigate the relation of entrainment between heart rate and brainwave. The preprocessing method is used same as the paper written by Aizawa et al. (2017) [70]. FFT is employed to transform data detected from the heart rate sensor and brainwaves sensor to PSD, then calculate the similarity of signals between subjects by PCC. In the experimental condition, the experimenter imitates the subject's actions, articulation, and voice volume when talking about a comm-on interesting topic. On the other hand, in the control condition, the experimenter behaves opposite to the subject's actions, articulation, and voice volume. Their heart rate and brainwave are collected during the experiments and analyzed by Pearson Correlation Coefficient (PCC) as the assessment method. The results show the delay of the physiological signal entrainment from heart rate (LF/HF ratio) to brainwave (Beta/Alpha ratio) is around 40-60 seconds, and the brainwave response speed is faster and more sensitive than the heart rate. However, there is no significant difference between the result with imitation behavior and that in the control condition, which implies simply imitating a partner is not enough for promoting entrainment.

3.1 Observing Relation between Heart Rate and Brainwaves & Effect of Imitation

In the age of AI, it is imperative to delve into the realm of robots and how they can bring improvement to human lives and human-robot interaction (HRI). With the continuous progress of AI, repeatable jobs have been gradually replaced such as cashiers, fast food waiters, phone receptionists, etc. Teachers, psychologists, medical workers, and engineers are jobs that we view as being impossible to replace, but this does not mean we cannot incorporate AI into these jobs and improve our working efficiency. This experiment observes the relation between two physiological signals which employed in entrainment assessment, brainwaves and heart rate, in the entrainment phenomenon. The entrainment of heart rate is discovered in Aizawa et al. (2017) [70], this experiment observed whether the brainwaves have entrainment by the same analysis method. The other is to observe whether imitation promotes entrainment occurs between humans, and try to employ this phenomenon to improve the relationship which needs communication or interaction. In 2003, research by Kory Floyd and Larry A. Erbert [101] demonstrated that when a person is interested in another person, they will be inclined to imitate the actions and poses of the party they're interested in. This experiment strives to verify that if both sides are interested in each other, whether they will be able to act in entrainment through imitation to promote entrainment occurs. To test out whether this works, first is to find out a common interest in a certain subject between two people, then to collect data on the heart rate and brainwaves of these two people under two circumstances, forced imitation and differentiation.

3.2 Experiment Design

The experiment was set up in two different situations, in the first experimental situation, I set subject A to imitate subject B's actions, articulation, and volume on a common interesting topic, and monitor their heart rate and brainwaves. In the second situation, I set subject A to differentiate (not imitate) subject B's actions, articulation, and volume while monitoring their heart rate and brainwave. A prerequisite investigation is undertaken to reach an understanding of the interests of each test subject before the experiment, the experiment figures are shown in Fig. 3.1 and Fig. 3.2. During the experiment, both test subjects wear an Arduino Heart Rate Sensor shown in Fig. 2.3 and Muse shown in Fig. 2.1.

Subjects wore a heart rate sensor on the ear to collect heart rate data. The heart rate data with RR intervals at a sampling rate of 1Hz is analyzed. In order to analyze the shift in heart rate intervals, I used the Fast Fourier Transform (FFT) to transform it. It is defined as 3.1

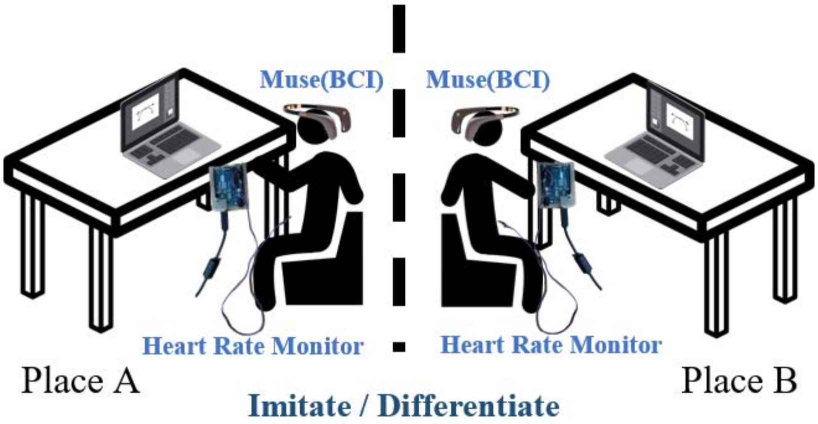


Figure 3.1: Experiment Schematic

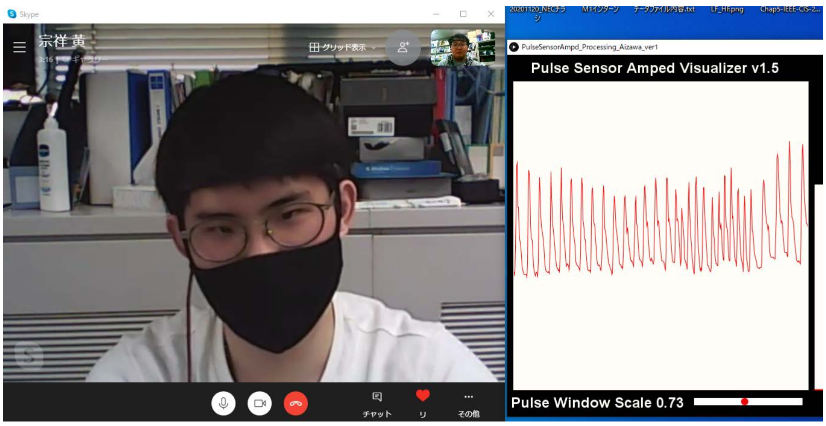


Figure 3.2: Experimental picture

$$X(\omega) = \int_{-\infty}^{\infty} x(t)\, e^{-j\varphi t} dt \tag{3.1}$$

The power spectral density is processed by FFT from RR interval data at 100 data window size and a shifting size of 1 data, then used SMA to smooth it with a 25-data window size to obtain a clear variability of the LF/HF ratio. The Pearson correlation coefficient is applied to find the correlation of the LF/HF ratio between the subjects. When Pearson correlation is above 0.9, the results are matching as shown in Fig. 3.3- 3.4.

Once the test subjects reach a consensus on their topic of interest, they will undergo two situations where they imitate and differentiate with each other on articulation and voice volume of speech and actions, actions include leaning forward and backward of the body, condition as shown in Table 3.1, and the experimental picture as shown in Fig. 3.2. To start

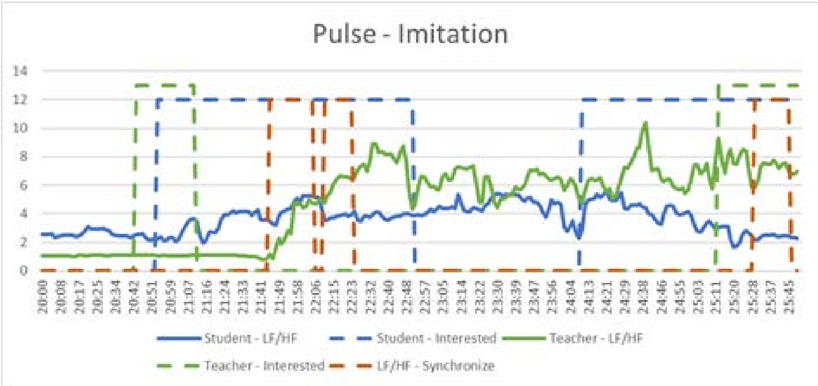


Figure 3.3: Pulse - Imitation

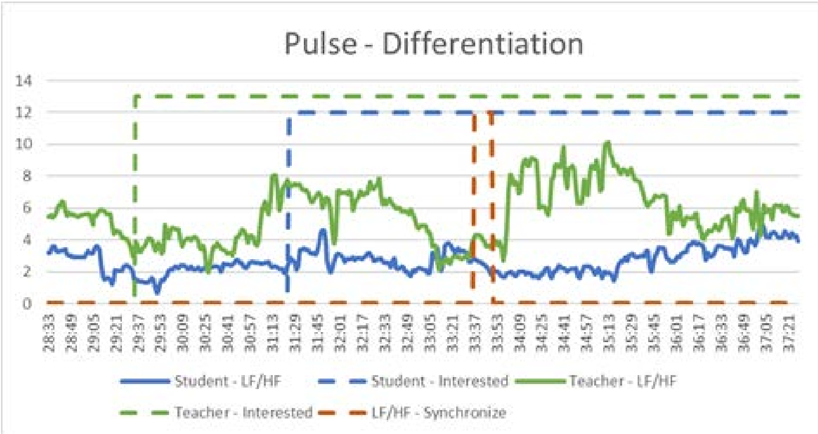


Figure 3.4: Pulse - differentiation

the experiment, the test subjects will press the button to start recording, the green and blue dotted lines as shown in Fig. 3.5- 3.8. The red dotted line is the result of calculating the correlation between the LF/HF ratio with a correlation above 0.9. The black dotted line is the result of calculating the correlation between Beta/Alpha waves with a correlation above 0.9. If the correlation of 0.9 continues for above 3 seconds, the entrainment is identified.

Table 3.1: Imitate condition

Body movement	Lean forward	Lean backward
Voice Volume	Increase	Decrease
Articulation	Fast	Slow

3.3 Results

In this experiment, 8 sets of data are gathered, and to prevent noise clutter, loose connection, etc. Each set was recorded for 10 minutes, then filtered down to 5 minutes or so. I used two viewpoints to assess the data, “Entrainment through Imitation” and “Relationship between Heart rate and Brainwaves Entrainment.” Results from analytical methods are shown by pair C and pair D. Fig. 3.5 is the imitation data from pair C. Fig. 3.6 is the differentiation data from pair C. Fig. 3.7 is the imitation data from pair D. Fig. 3.8 is the differentiation data from pair D. The blue line is the brainwave curve from the student (imitator), this curve is the moving average after being smoothed with a 25-second window size while the green line is the brainwave curve from the teacher (imitated). Brainwave entrainment is shown within the black dotted lines. Heart rate entrainment is shown within the red dotted lines.

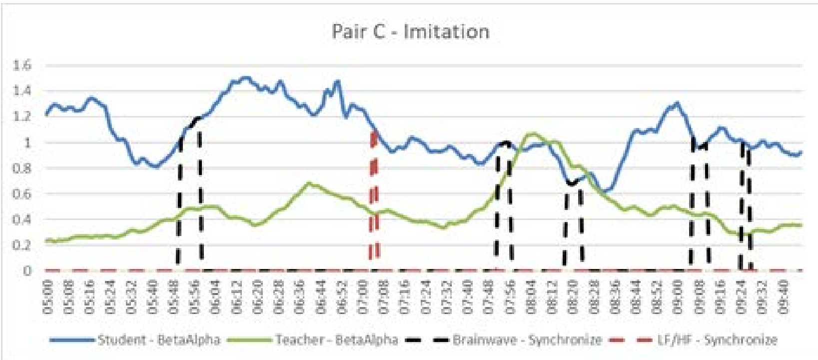


Figure 3.5: PairC imitation

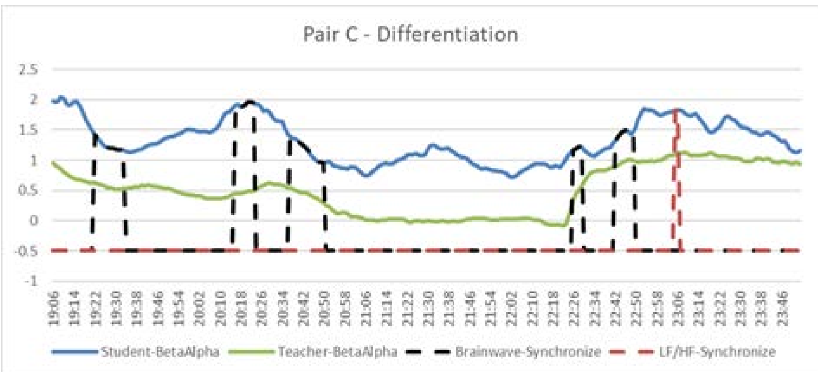


Figure 3.6: PairC differentiation

To observe whether entrainment is achieved, Table 3.2 shows the 8 sets of data through

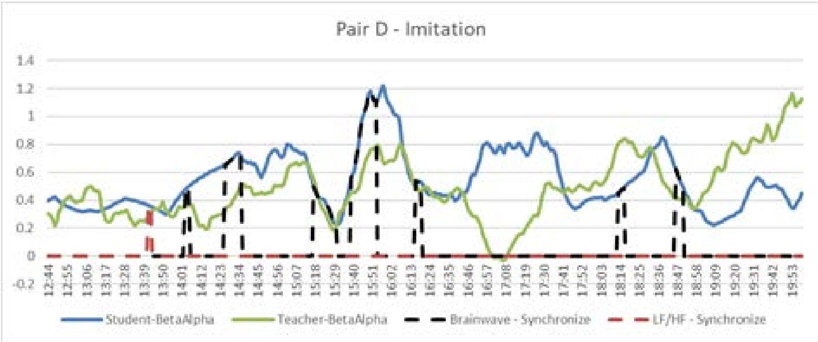


Figure 3.7: PairD imitation

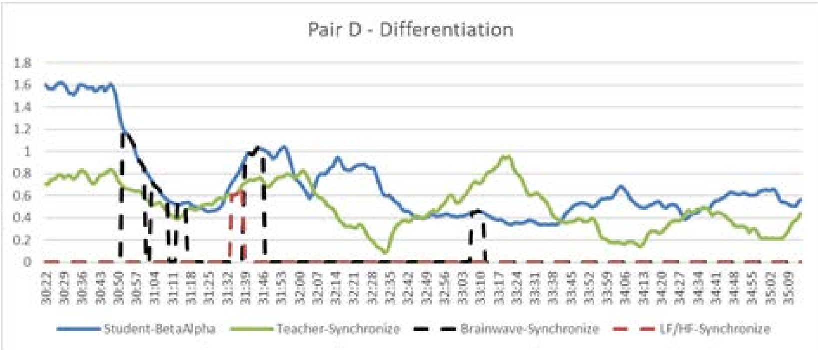


Figure 3.8: PairD differentiation

different categories, imitation, and differentiation, the number of times entrainment is achieved in heart rate and brainwaves. The data shows that imitation of body tone or language does not affect brainwaves as shown in the results where brainwaves and heart rate have no increase. From the amount of entrainment in brainwaves, there are 4 sets of data in which imitation is higher than differentiation and 4 sets of data in which differentiation is higher than imitation. For the amount of entrainment in heart rate, there are 3 sets of data in which imitation is higher than differentiation, while 5 sets of data in which differentiation is higher than imitation. From the results, there is no increased rate of entrainment within the heart rate and brainwaves are analyzed.

Due to brainwave entrainment might being more sensitive than heart rate entrainment, heart rate entrainment is used as a base to calculate whether brainwave entrainment appears before or after, then calculate the time difference. Fig. 3.9, Pair E shows entrainment based on imitation, and Pair H, Fig. 3.10 shows entrainment based on differentiation. The similarities using color-coded circles for each pair are analyzed. I discovered that in the results,

Table 3.2: Results of Entrainment within Brainwaves and Heart Rate

Imitation / Differentiation	Times Brainwaves are entrainmented	Improvement	Times Heart Rate are entrainmented	Improvement
Pair A	4 / 2	O	3 / 1	O
Pair B	5 / 4	O	3 / 2	O
Pair C	5 / 5	X	1 / 1	X
Pair D	5 / 5	X	0 / 1	X
Pair E	7 / 5	O	2 / 2	X
Pair F	5 / 11	X	1 / 1	X
Pair G	4 / 4	X	1 / 0	O
Pair H	5 / 4	O	1 / 4	X

the β/α ratio from brainwave entrainment appears approximately 40 to 60 seconds before LF/HF ratio from heart rate entrainment 14 times out of 22 times with a possibility of 64%.

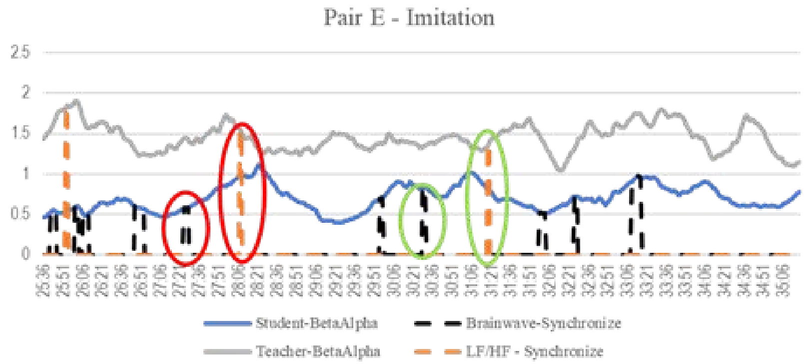


Figure 3.9: PairE imitation

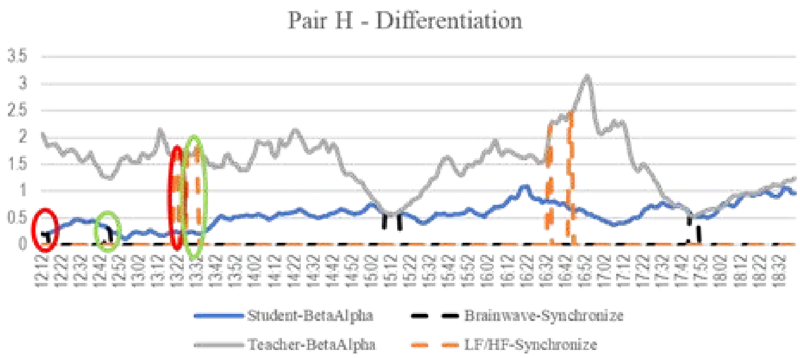


Figure 3.10: PairH differentiation

3.4 Summary

In “Entrainment through Imitation”, it is present cannot be proved due to differences in imitation ability, the mental state and sex of the subject, and other possible factors that may affect the data. In the future, this experiment will attempt to remove these factors to prove that entrainment through imitation is possible. From “Relationship between Heart Rate and Brainwaves Entrainment”, I deducted from the experiment results that brainwaves are more sensitive than heart rate as shown from the 8 sets of data. Entrainment from brainwaves is more frequent than heart rate, and not only the frequency but the speed at which entrainment is reached is also faster by approximately 40 to 60 seconds. In this experiment, I tried using imitation to improve entrainment, but the effectiveness was bad. Therefore, employing Kebbi to affect the subject’s emotions is planned in the next experiment.

Chapter 4

Observation of Robots with Different Expressions towards Entrainment Robots

In the world, the development of many countries and places is different, there are educational gaps between rural and urban areas. Due to rural areas' slow development, the infrastructures are worse than in urban areas, and the willingness of teachers to teach in such areas is significantly reduced in comparison to more urban areas, gradually causing the problem of lacking teaching personnel in rural areas.

To deal with this situation, several scholars began to attempt to teach students through robots. Lee et al. use the Kebbi robot to apply Human-Robot Cooperative Edutainment as a robot teacher in a number of elementary schools, junior high schools, and at a university [102] - [105]. This experiment wants to research human-robot interaction, using body language, voice, and facial expressions for robots (teacher) and humans (student) to reach good communication status, and improve learning performance and learning motivation.

The purpose of this experiment is to observe whether robot expressions are affecting subjects' stress and physiological status during the exam. This project proposed two kinds of robot expressions in this experiment, robots express themselves differently when subjects answer correctly or incorrectly. Subject heart rate and brainwaves are monitored by sensors during the experiment. The experiment discovered when subjects face hard questions and answered incorrectly, there are different fluctuations in subject stress. This proves that robot expressions influence subject stress under different situations which in turn be applied as a feedback mechanism for influencing stress with students, and in the future can support humans as assistants.

4.1 Humanoid Robot

Robots are a way of saving and replacing human resources. In simple things, robots can be used to replace human resources; In complex things, robots can be used to assist humans. Compared with non-human robots, the appearance of human robots is more likely to cause changes in human hearts, because humanoid robots are able to express human emotions through expressions, voice, and movements.

Considering that robots will be used in various types of situations in the future, I aimed to choose a robot that is suitable for use in various scenarios, looks friendly, and is not intimidating. Compared with Pepper [106], Nao [107], or some other robots, Kebbi has a more friendly appearance. The Kebbi robot—made by NUWA Robotics—is 318 x 307 x 166mm, which is suitable for being used in the traditional classroom or directly participating in a group discussion at the table. Moreover, NUWA Robotics provides a convenient platform for coding a program; Blockly is used on the platform for coding purposes [108]. If it is to be widely used in education in the future, even teachers without a foundation or knowledge of programming can program robots that supplement their teaching materials. Therefore Kebbi is chosen to participate in experiments as an intermediate that included the experiments in Chapter 4 and Chapter 5, the actual application between the Kebbi robot and humans is shown in Fig. 4.2.

Figure 4.1: Kebbi robot

Kebbi is designed that behaves with the same emotion as the subjects in this experiment. When subjects answered correctly, the robot will react with facial expressions, body lan-

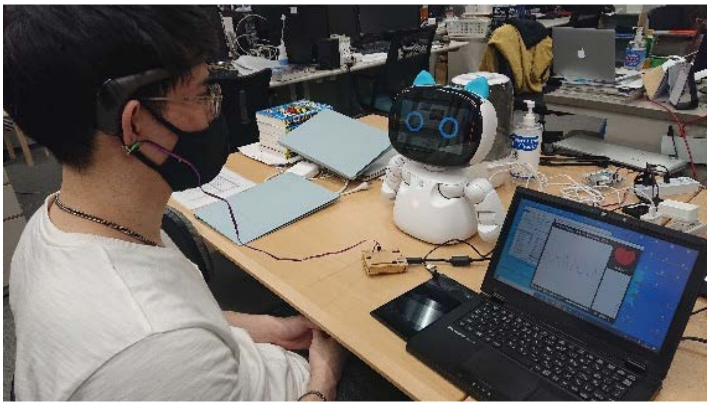


Figure 4.2: Interaction between Human and Robot

guage, and happy emotions shown as in Fig. 4.3. When subjects answered incorrectly, the robot will react with facial expressions, body language, and sighing to behave in frustrating emotions shown as in Fig. 4.4.

Firstly, in order to verify whether facial expressions, body language, and voice affected subjects or not, the control group and experimental group are set to conduct a test consisting of ten questions. I split the feedback of robots about the ten questions into groups including expressions and excluding expressions. The groups with expressions and without expressions are set up in the first five questions and the last five questions respectively. Robots with expressions in the first five questions and without expressions in the last five questions are set as Situation A. On the other hand, Robots without expressions in the first five questions and with expressions in the last five questions are set as Situation B. In the previous experiment, people will not perceive the expressions changing of a robot in situation A is discovered, but in situation B, people easily perceived the change in the expression of robots. Therefore, let the robot with expressions on the last five questions as the focal point to show the change in expression is decided.

Figure 4.3: Happy expressions

Figure 4.4: Sad expressions

4.2 Quiz Design

In the quiz design of the experiment, there are only two possibilities of answering right and wrong, two kinds of expressions to correspond are used. In order to achieve emotional entrainment, I want the robot to show the same emotional performance as the subject. Therefore, the robot will be happy when the answer is correct, and the robot will be sad when the answer is wrong, through this way achieves emotional synchronization between the human and robot, while observing the impact of this approach on the stress of subjects.

There are ten math questions, and there are two kinds of difficulty of questions, easy and advanced. In order to observe the change in data fluctuations, the difficult questions as the first three questions and the last three questions and put easy questions between them are set up. The purpose of this design is to evaluate the change in stress when subjects are facing hard questions or subjects answer incorrectly. Due to the difference in math ability, subjects to fill out questionnaires after an experiment to confirm their opinion on the questions asked.

4.3 Experiment Design

The purpose of this experiment is observing robots can through expressions, body language, and voice affect humans or not. Subjects were asked to wear a heart rate sensor and brainwave sensor in the experiment and asked to rest one minute before the experiment started to calm their heart rate and brainwave, after that, the robot will ask math questions by true-false. After each question is narrated, the subject is restricted to answering within 8 seconds. After the end, the subjects were asked about their subjective thoughts on the difficulty of the questions. When analyzing the data, I especially observed whether there are any special changes before and after the subjects encountered simple and difficult problems. The experimental procedure is as follows.

1) Rest for a minute.

2) Touch the head of the Kebbi robot to start the quiz.

3) Describe math questions.

4) Answer each question within 8 seconds.

5) Ask subjects to do a questionnaire about the difficulty of the quizzes after finishing all

quizzes.

There were five people participated in this experiment, but the sensors did not work smoothly, and some data was unusable, therefore, two sets of data are used as the result. Subject A is a 27-year-old female. Subject A is who has been in contact with robots for a long time. She has exposure to many robots, such as Pepper, Nao, etc., and she also has frequent exposure to Kebbi robots before the experiment. Subject B is a 25-year-old female. She has only exposure to two robots, Pepper and Kebbi, and she had 1-2 exposures to the Kebbi used before the experiment.

4.4 Results

In Fig. 4.5 and Fig. 4.6, the vertical axis shows LF/HF ratio, and the horizontal axis shows time. Blue lines show the LF/HF ratio and Beta/Alpha ratio. The black lines are shown as the time when the subject is privy to robotic feedback, as well as the time at which the subject is answering questions. The red H is when the subject feels that question is hard, and the red X is where the subject answered incorrectly. The red dotted line divided the results when the robot has expressions and without expressions. The circles in the figure are shown when the subject is faced with difficulties and answers incorrectly, the orange circle is shown when both pulses and brainwaves show a decrease while the green circle is shown where both pulses and brainwaves show an increase.

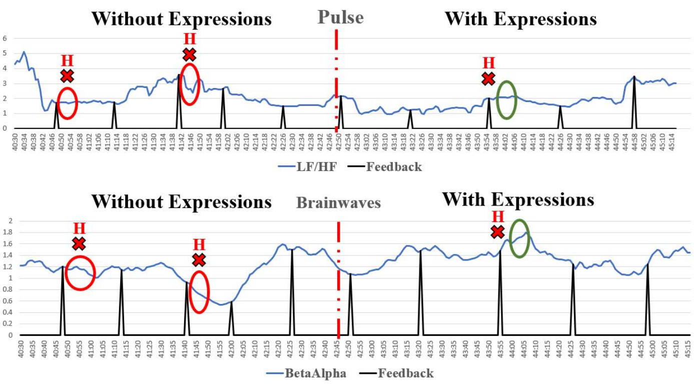


Figure 4.5: Fluctuations of Pulse (upper) and brainwaves (lower) – Subject A

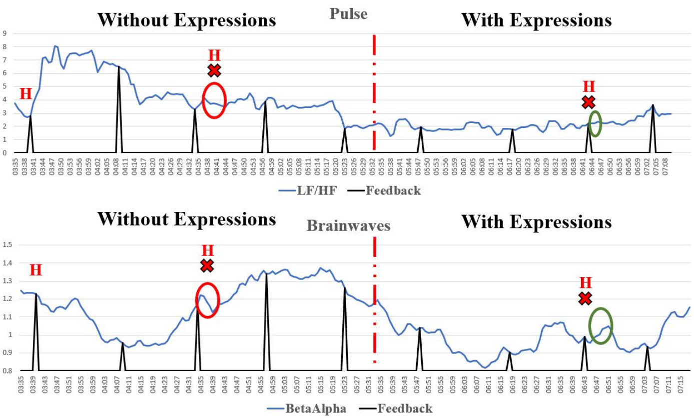


Figure 4.6: Fluctuations of Pulse (upper) and brainwaves (lower) – Subject B

4.5 Summary

From the results, it is concluded that when the subject answered incorrectly and without feedback from the robot, the subject exhibits no increased stress, as shown in the orange circle. However, when the subject answered incorrectly and the robot showed expressions such as sighing or dejection, the subject exhibits increased stress, as shown in the green circle. Robotic feedback influences stress are inferred from the analysis by the brainwave and heart rate fluctuations. The next step is to group robots and humans to conduct cooperation and observe if robots can promote physiological entrainment during cooperation, to deduce whether students put their heads together when they are facing questions. Through robot-human cooperation, this project hopes that robots can contribute to the field of education, to assist teachers in areas where there is a lack of teaching personnel.

Chapter 5

Observation of Human Entrainment with Robot Assistance towards Education

To ensure the complexity of this experiment, crosswords were used for this task, which subjects were required to complete in cooperation with each another. At different points in time, the robot would use different expressions, actions, and words as reminders or hints, aiding communication and better cooperation between subjects. The timing of the robotic reminders, entrainment, conversations between the subjects in the crossword tasks, and the completion rate of the crossword puzzles were recorded. The average completion rate improved by 10% with the aid of the robot, as opposed to not using the robot. The results of this study prove that robotic participation in human interaction is beneficial and that implementing robotic assistance will improve human-human interaction.

5.1 Application of Entrainment Promoting Robot

After investigating the relation of entrainment between heart rate and brainwave which is described in Chapter 3 and confirming the effectiveness of a robot for affecting the internal state of a human which is described in Chapter 4. This chapter describes the application of entrainment promoting robot, and analysis of employing the assessment method of the entrainment which described in Chapter 2.

The milestone of this dissertation is the entrainment promoting robot that encourages interpersonal entrainment through dialogue and expressions developed which is described in this chapter. An assessment method of entrainment employing DTW to analyze PSD data from heart rate and brainwaves are used in this experiment. This experiment was conducted with two subjects in each experimental group. One subject holds a clue and the other fills a crossword grid respectively, and they communicate and cooperate to complete the crossword in a limited time. In the experimental condition, the robot tells the subjects the time with different dialogues and expressions of anxiety. The control condition is conducted without the robot.

The subject tended to talk more frequently in the experiment with the robot than in the control condition is observed, which indicates using the robot as an intermediator is helpful for human communication and for improving the performance of cooperation. In terms of the entrainment assessment, it was confirmed that different from regular synchronization that is the phenomenon observed at the same time, the physiological entrainment between humans observed in the experiment had a "time delay": the entrainment of partners (collaborators) was observed in the same time segment, but not at the same time.

5.2 Experiment Design

This experiment aims to use robots to enhance the entrainment phenomenon between people during cooperative tasks to improve work efficiency. To ensure the complexity of the cooperative task, crossword puzzles are chosen as the task. Eight subjects—aged between 22 and 27 were selected and divided into four groups. Three tasks are prepared and let the subjects rest after every task. One subject held the clues, as shown in Fig. 5.1, while the other held the crossword grid, as shown in Fig. 5.2. The subjects discussed and finished the crossword.

タテのカギ:

2	イエスキリストの誕生を記念する祝祭。十二月二十五日。
3	外出して家にいないこと。
4	目を動かさないで見ることのできる範囲。
5	話や音楽を聞く人。聞き役。
7	競馬などの馬の乗り手。
9	めぐり合わせ。ラッキー。
11	電信・電話・放送などを受けること。
12	梅の実を氷砂糖と一緒に焼酎につけて作ったお酒。
13	年長者や先輩を呼ぶ言葉。
15	仕事の合間のひま。仕事を離れて自由に使える時間。

ヨコのカギ:

1	ペダルを踏むと速度が増す加速装置。
4	計算の順序や関係・法則などを記号や数字で表したもの。
6	牛肉にネギ・豆腐などを添え、醤油・砂糖・みりんなどで味付けしながら煮焼きした鍋料理。
8	数が多いこと。
10	小麦粉・そば粉などを練って皮とし、中にあんを包んで蒸し揚げたお菓子。
13	今日の次の日。
14	手術に使う切れ味のいいナイフ。
15	よいことと悪いこと。善悪。
16	体が非常に大きい男性。大男。
17	湯などから立ちのぼる水蒸気が冷えて、白い煙のように見えるもの。

Figure 5.1: Crossword Clues

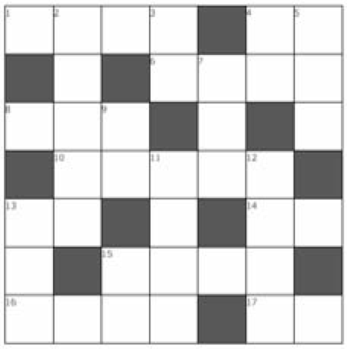


Figure 5.2: Crossword Grid

In order to overcome the challenge of different proficiency levels between native Japanese speakers and foreigners, it was decided that the person who would deal with the clues, in each group, would be Japanese. The completion rate is used as a performance standard and not the correct rate. during the experiment, the subjects wore the Muse sensor and sat face-to-face. The Kebbi Robot was positioned between the subjects, as shown in Fig. 5.3During the experiment, the subjects' brainwaves and the number of times dialogue between subjects are recorded. Three crossword puzzles were prepared as cooperative tasks, with each task having a time limit of ten minutes; furthermore, one minute was allotted for the subjects to relax after each cooperative task, as shown in Fig. 5.4. Therefore, the average duration of the experiment for each group was about 32 minutes. In each task, when at the second minute, fifth minute, and eighth minute, the robot would speak, giving different dialogues with different expressions to show varying degrees of anxiety, as shown in Fig. 5.5. The details of the dialogues and expressions of the robot are shown in Table 5.1. Two groups: the experimental group, which does the cooperative task with robot participation, and the control group, without a robot, were set up.

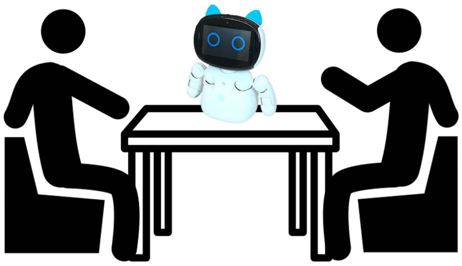


Figure 5.3: Situational Simulation

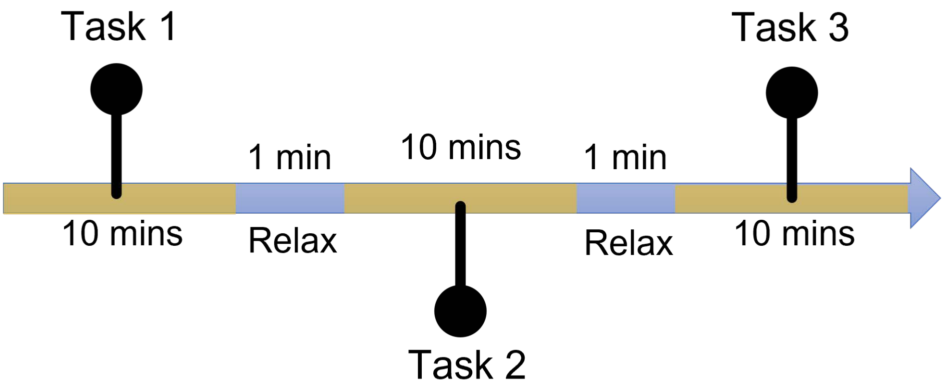


Figure 5.4: Experiment Flow

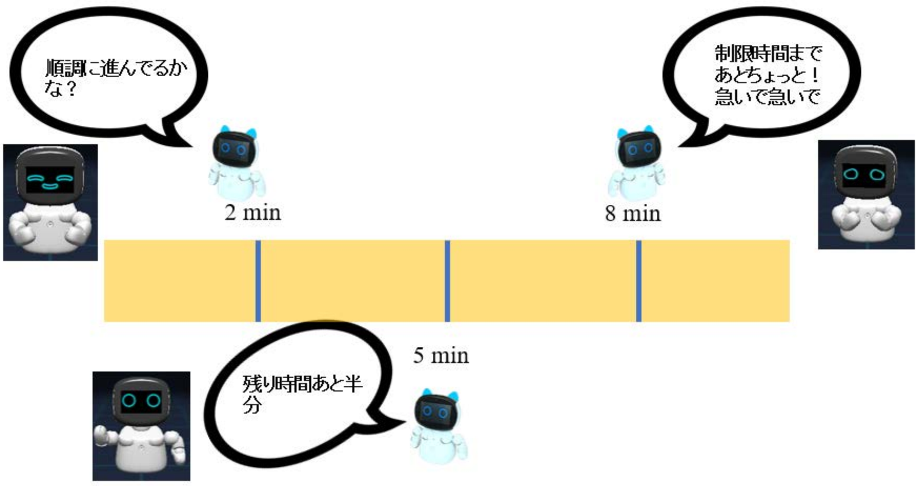


Figure 5.5: Each Task in Experiment

Table 5.1: Expressions and Dialogue

Expressions	Dialogue (Japanese)	Dialogue (English)
	順調に進んでるかな？	Is it going well?
	残り時間あと半分	Half the time left.
	制限時間まであとちょっと！急いで急いで	The time is almost up. Hurry up! Hurry up!

5.3 Results

The Muse sensor analyzed the data by the DTW algorithm, and the results of each group are shown in Fig. 5.6-5.9. The "a" part of the figures represents the task done with Kebbi, the robot, and the "b" part of the figures represents the task without Kebbi. The blue lines represent subject A's β/α ratio, while the red lines are subject B's β/α ratio, the green dotted lines are the entrainment parts of subject A, the purple dotted lines are the entrainment parts of subject B, the orange lines are the timings of the robot's reminder, and the bright blue lines are the timing of start and end of the experiment. The entrainment times for each group, with and without the robot, are shown in Table 5.2.

A comparison of the two groups shows that when there was robot participation, the duration of entrainment was relatively more. I think it is because, during the experiment, the robot adopted a happy tone at the beginning, reminded the subjects when half the experiment time was over, and urged the subjects anxiously toward the end to complete the task. Thus, it appears that the application of continuous pressure upon the subjects more often led to the relaxation of the state of entrainment. The change of the β/α ratio average before and after the reminder for 30 seconds are compared. In addition to the number of changes in the subjects, the number of times is also calculated that the β/α ratio increased and decreased simultaneously. The four groups are found, the number of times that the β/α ratio increased simultaneously after the reminder was more than the number of times it decreased, as shown in Fig. 5.6. Therefore, I consider that the reminder of the robot does help the subjects to reduce relaxation and focus more on the task.

Based on these four sets of experimental data, the effect of robots on the occurrence of the entrainment phenomenon varies in degree for different people is hypothesized. For example, groups A and B are less affected, and groups C and D are more affected. Considering the differences in age and gender, the influence of gender be ruled out. Finally, the subjects in this experiment all knew each other but were not particularly familiar with each other. In terms of age, the age difference who participated in Group A was 3 years, the age difference who participated in Group B was 1 year, the age difference who participated in Group C was 1 year, and the age difference between those who participated in Group D is 3 years. In terms of the affected size group, the difference in age between both groups was 1 and 3 years, respectively; therefore, the influence of age also be ruled out, as shown in Table 5.3.

Conversely, regarding the subjects' number of times of dialogue, when there was a robot, the subjects communicated more. This may be because of the robot's constant reminder timing, which made the subjects cooperate more actively in answering the questions. The number of times subjects' dialogue is shown in Table 5.4.

Table 5.2: Entrainment Times of Groups

Entrainment Times	GroupA	GroupB	GroupC	GroupD
With Robot	3	3	6	8
Without Robot	1	3	3	3

In the experimental results, the entrainment and dialogue times in each experimental group are calculated. From the statistical results, in each group of experiments, the times of brainwave entrainment of robots are more than or equal to those of the control group without robots; even the times of dialogue are the same. Although during brainwave entrainment, not every group of experiments with a robot is more than the case without a robot, which proves that the robot's participation has a specific influence on the entrainment, some groups possessed the same times of brainwave entrainment. Therefore I think the effect may vary from person to person. In contrast, the data shows that in cooperative tasks, the participation of robots does promote people's communication and entrainment. In the resulting statistics, the average completion rate of tasks with robots is 92%, and the average completion rate of tasks without robots is 82%, as shown in Table 5.5. There is an increase of 10%, which proves that using robots is helpful for cooperative tasks.

Table 5.3: Gender and Age of Groups

	Group A (Subject1/Subject2)	Group B (Subject3/Subject4)	Group C (Subject5/Subject6)	Group D (Subject7/Subject8)
Gender (Male/Female)	M/M	F/M	M/M	F/M
Age	25/22	27/26	23/22	25/22

Table 5.4: Number of Times Subjects' Dialogue of Groups

Dialogue	Group A (Subject1 / Subject2) (First - Second - Third Task)	Group B (Subject3 / Subject4) (First - Second - Third Task)	Group C (Subject5 / Subject6) (First - Second - Third Task)	Group D (Subject7 / Subject8) (First - Second - Third Task)
With Robot	38/37 - 37/37 - 42/40	37/36 - 37/35 - 41/35	44/49 - 35/41 - 40/50	29/29 - 28/26 - 29/27
Without Robot	28/29 - 30/36 - 35/36	29/32 - 29/30 - 29/29	30/32 - 34/36 - 37/42	18/18 - 23/26 - 17/19

Table 5.5: Completion Rate of Groups

	Group A (First - Second - Third Task)	Group B (First - Second - Third Task)	Group C (First - Second - Third Task)	Group D (First - Second - Third Task)
With	94% - 100% - 94%	94% - 100% - 82%	100% - 95% - 94%	82% - 75% - 88%
W/O	78% - 78% - 83%	74% - 78% - 78%	96% - 72% - 94%	96% - 83% - 72%
With (AVG)	96%	92%	96%	82%
W/O (AVG)	80%	76%	87%	84%

Table 5.6: Brainwave Fluctuation of Before and After Reminder

(a) Synchronized Times of GroupA

GroupA - β/α	SubjectA	SubjectB	SubjectA & SubjectB
↗	5	5	4
↘	4	4	3

(b) Synchronized Times of GroupB

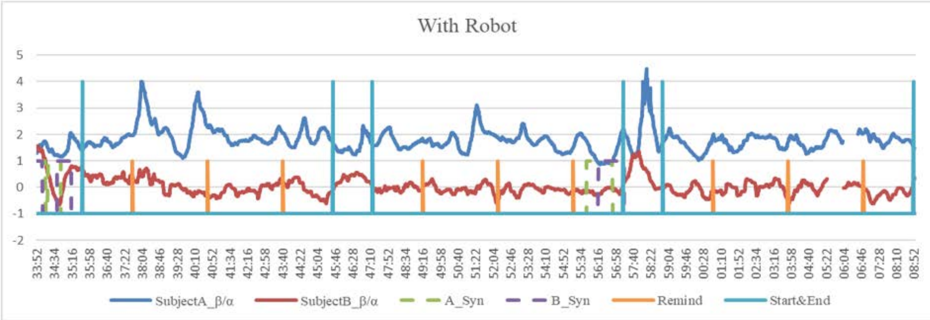
GroupB - β/α	SubjectA	SubjectB	SubjectA & SubjectB
↗	8	4	4
↘	1	5	1

(c) Synchronized Times of GroupC

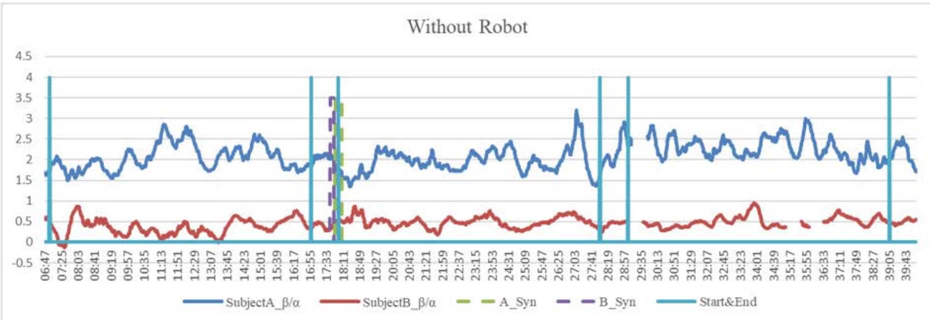
GroupC - β/α	SubjectA	SubjectB	SubjectA & SubjectB
↗	7	3	2
↘	2	6	1

(d) Synchronized Times of GroupD

GroupD - β/α	SubjectA	SubjectB	SubjectA & SubjectB
↗	8	3	3
↘	1	6	1

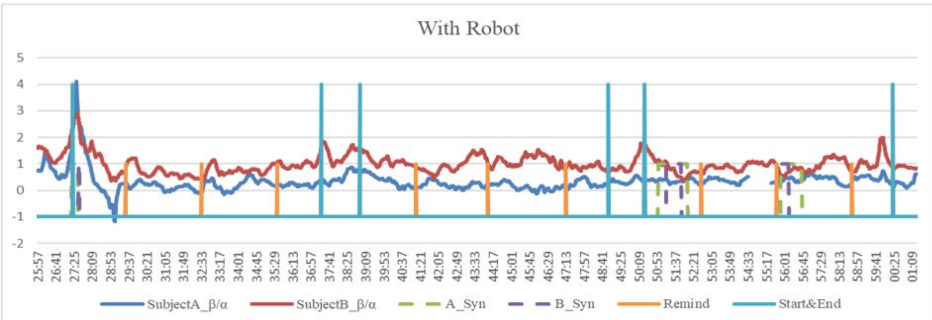


(a) With Robot

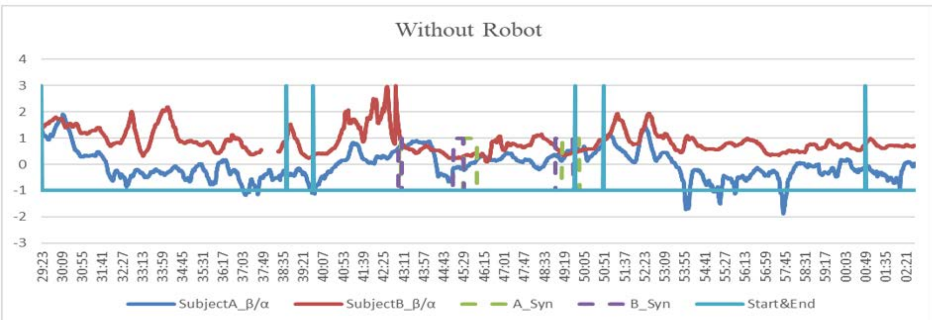


(b) Without Robot

Figure 5.6: Group A Result

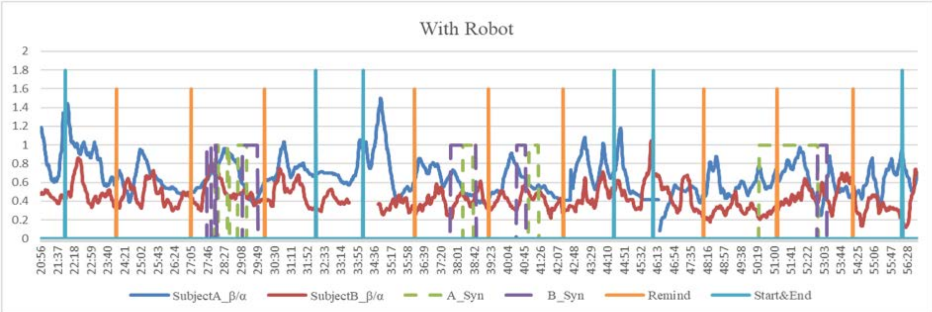


(a) With Robot

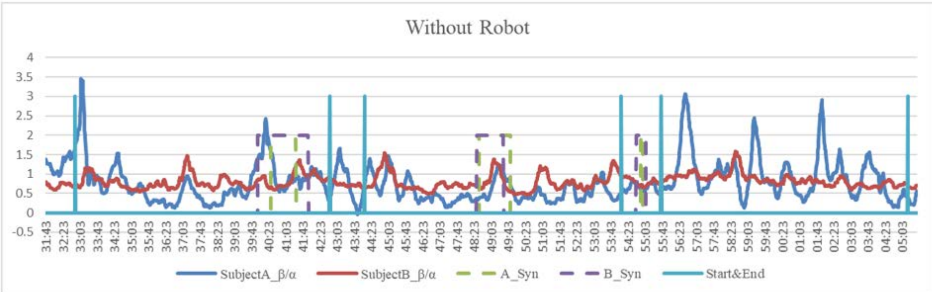


(b) Without Robot

Figure 5.7: Group B Result

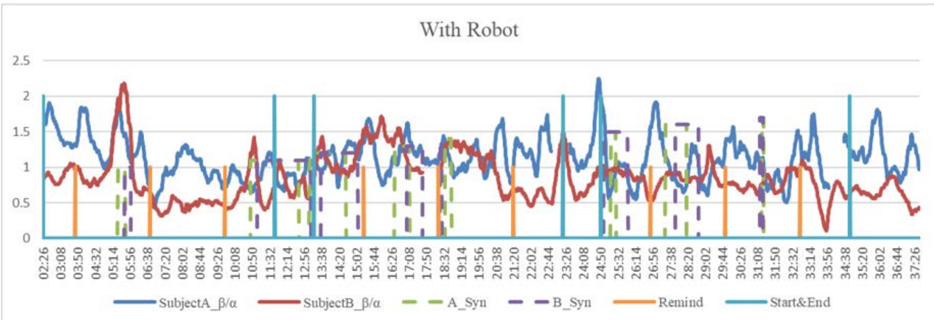


(a) With Robot

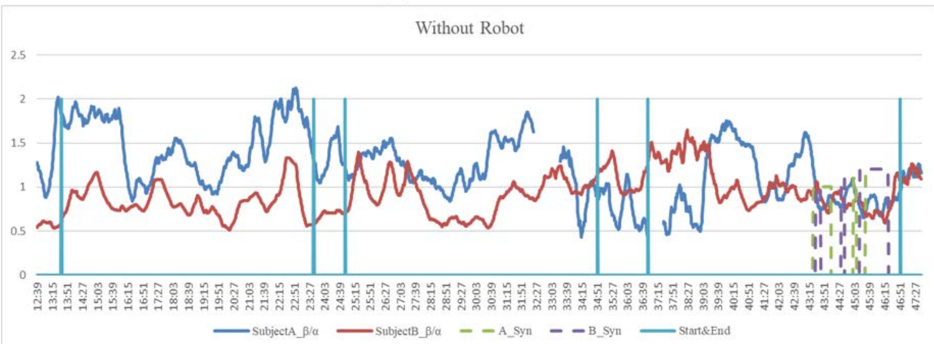


(b) Without Robot

Figure 5.8: Group C Result



(a) With Robot



(b) Without Robot

Figure 5.9: Group D Result

5.4 Summary

Cooperation and group learning one of the essential points in human-human communication, and in this research, I observed human-human interaction through cooperative problem-solving with robotic reminders to improve problem-solving efficiency, with the ultimate goal of enhancing human-human cooperation. With further investigation of human-to-human cooperation, the phenomenon of entrainment between the two subjects is noticed; To further improve the success of entrainment, this experiment used Kebbi to give suggestions, hints, and reminders to the subjects of the time left to complete the crossword puzzle, which showed a 10% improvement in performance. Usually, during the experiment, the two subjects would be working with each other, face-to-face. However, owing to COVID-19, the experimental groups were limited in selection, and I hope to collect more data in the future to prove results of this study can be applied to general education. Our long-term goal is to invent more solutions with robotic assistance in cooperation and create a new frontier for cooperation improvement through the entrainment amongst humans with robotic assistance.

Chapter 6

Conclusion

6.1 Conclusion of Chapters

This dissertation proposes a new application for robots to assist humans' cooperation. This research proposes an "entrainment promoting robot" which promotes interpersonal entrainment and assists cooperation among humans, which smooths communication by participating as an intermediary. I pursued three considerations in this dissertation; first, it is confirmed that the heart rate and brainwaves have the same entrainment phenomenon; second, it is confirmed that a robot affects the internal state of humans through expressions and dialogues of it; third, ascertain an assessment method of physiological signal entrainment considering delay which is contained physiological signal. Chapter 2 describes "Entrainment promoting robot" and "entrainment assessment method". Chapter 3 which observed the relation between heart rate (LF/HF ratio) and brainwave (Beta/Alpha ratio) and discovered the delay between them around 40-60 seconds; Chapter 4 which discovered that according to different feedback from the robot, the human has different psychological changes, significantly when a subject answered incorrectly; Chapter 5, which applying entrainment promoting robot to interpersonal interaction. The results show that the complete rate of task and frequency of communication is improved.

Chapter 2 presents the main concept of this dissertation, physiological entrainment, and introduces relevant works of literature that support the motivation of this dissertation. Finally, the assessment method used and the results are described. Chapter 3 presents in terms of "Relationship between Heart Rate and Brainwaves Entrainment", brainwaves are deducted that it is more sensitive than heart rate. Entrainment from brainwaves is more frequent than heart rate, and not only the frequency but the speed at which entrainment is reached is also faster by approximately 40 to 60 seconds. Chapter 4 presents the possibility of using the Kebbi robot to affect a human's internal state. From the results, it is concluded that when the subject answered incorrectly and without feedback from the robot, the subject exhibits no increased stress. However, when the subject answered incorrectly and the robot showed expressions such as sighing or dejection, the subject exhibits increased stress. Chapter 5 presents entrainment robots that promote the frequency of physiological entrainment and cooperative performance. The Kebbi is used to give hints and reminders to the subjects of the time left to complete the crossword puzzle. The results showed a 10% improvement in complete rate, and the interaction between the subjects is also more frequent.

6.2 Future Work

In terms of the entrainment assessment, different from regular synchronization at the same time, the physiological entrainment between humans assumed in this dissertation, the "time delay" (subject A's and subject B's entrainment are in the same time segment, but not at the same time) which is been verified, but it still needs more data to verify.

In terms of remain problem, first, the model answer of "physiological entrainment" does not exist now, how to determine and defined is the most important thing in future work. Second, I used "robot expressions (normal to worried)", and "robot dialogues (normal to worried)" to affect the internal state of humans to promote entrainment between humans in this dissertation. However, there must have other factors which promote the entrainment phenomenon, further research is needed on this term. Third, the brainwaves in entrainment are not classified. I hope to make video, audio, and brainwave recordings, simultaneously, in future experiments and classify the brainwaves of entrainment into several types by wave fluctuations. The interaction between the subjects can be analyzed to find out the correlation between the pattern of brainwaves and the behavior of the subjects in the entrainment phenomenon. The correlation between the entrainment of the body (blinking, etc.) are also could be explored, the entrainment of voices, and the entrainment of brainwaves. Finally, I used crosswords as a collaboration task to ensure the complexity of tasks in the final experiment, which subjects will think seriously, but the difficulty is not too hard to let subjects give up. Therefore, robot expressions and robot dialogues affect humans successfully. In the implementation of a real application, if the complexity of tasks is too complicated, or the difficulty of tasks is too hard for users, the result may differ, therefore developers need to consider a lot of factors in real education occasions and work occasions.

In the future, I hope to be able to detect and process physiological information currently, let the robot understand the current physiological state of the user, and do real-time feedback, the BCI is chosen (Muse) which brainwaves sensor uses dry electrodes can make full use of advantages, that can be applied in actual occasions easily. In view of my own background (master degree's research, parents are teachers, etc.), Children are the future of humans, and a good education can benefit the development of humans, therefore, I hope to first apply it in the field of education, subsequently, and then expand to various occasions. Confucius once said, "Teach in accordance with different aptitudes." The best way to teach students is to teach them on the basis of their aptitude. However, in reality, it is difficult to implement effective educational methods due to the lack of human resources in rural areas with a lack of access to educational resources. Utilizing of robot assistance can solve the problem of human resources lacking, furthermore reach the "Teach in accordance with different aptitudes," but to reach the above level, I believe that it must be combined with more knowledge of education experts and even educational psychology, etc. Therefore, it is foreseeable that there is still a long way to go in the future.

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Appendices

Appendix A

Appendix A The quizzes used in the experiment describes in Section 4.3

No.	Quiz	Difficulty
1	22×87	Hard
2	25×13	Normal
3	15×83	Hard
4	7×7	Easy
5	5×9	Easy
6	3×9	Easy
7	6×8	Easy
8	72×32	Hard
9	14×6	Easy
10	63×39	Hard

Appendix B

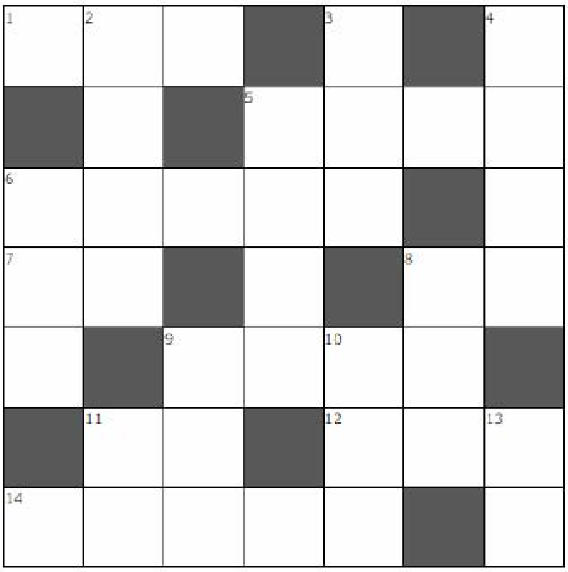
Appendix B The Crosswords used in the experiment describes in Section 5.2

タテのカギ:

2	一つのことに集中し、他のことを考えないさま。
3	住んでいる家。暮らしている所。
4	サッカー・ラグビーなどでボールをけりながら進むこと。
5	女性が結婚して夫の家に入ること。また、その儀式。
6	物事を行う場合に、守らなければならない決まり。規定。規約。
8	疲れて元気がなくなること。
9	農業のために使われる土地。
10	物や人を使うこと。用いること。
11	企業の資本の増減・出納などを一定の形式で記録・計算・整理する記帳法。
13	時間の差。標準時の違い。時間をずらすこと。

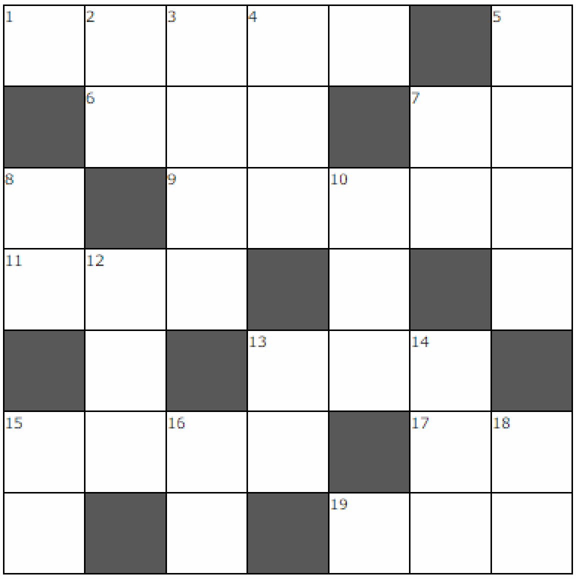
ヨコのカギ:

1	朝鮮の辛い漬物。
5	夜、警戒して見回ること。また、その人。
6	危険にさらされている人命を救うこと。
7	積み重なったもの。かさなり。
8	日の出から日の入りまでの間。正午、または正午すぎ。
9	紙をはり合わせるとき、のりをつけるために設けてある部分。
11	まっすぐで細長く手に持てるぐらいのもの。
12	しなければならない仕事。用件。
14	鉄道の駅の長。



2	無意識の習慣になっている動作や言葉。
3	ナラ、クリなどの枯れ木に生える食用きのこ。外面は褐色。肉は白色。
4	銀行などの金融機関に金銭を預けること。また、その金銭。
5	映画・テレビドラマなどの脚本。台本。
7	書かれた文字。書いてまとめた物。書物。
8	真の値と計算・測定して得た近似値との差。
10	蒸気の噴出によって音を出す仕組みの笛。またはその音。
12	限りがないさま。終わりのないさま。
13	国の最高権力者。君主。
14	六月から七月中旬にかけて降る季節的な長雨。つゆ。
15	仕事を仕上げるのに必要な時間や手数。
16	ほかのところ。別のところ。
18	音楽に合わせて体や手足を動かし、さまざまな姿を見せること。

1	大勢が声をあげていっせいに笑うこと。
6	西暦で年を百年ごとに区切って表す単位。
7	売っている物。商品。
9	短い距離。
11	ぞっとした寒さ。
13	物を置く場所。
15	本来の目的とは異なる別の用途に当てること。
17	ちょうど、この時。
19	二つの物・事柄の間に違いがあること。



タテのカギ:

2	量。音量。巻。
3	英語で好機・機会のこと。
4	男の子。少年。
5	儀式を行う場所。
8	ある物・人・事がらが、しめている場所。地点。
9	細かい石の集まり。小石に砂の混じったもの。
10	一般の小売店で売られていること。
12	税金をかけること。
14	繊維状のもの。細長い線状、糸状のもの。一続きにつながっているもの。

ヨコのカギ:

1	こうなりたい、こうしたいという強い願い。未来に対する明るい見通し。
5	水や湯を雨のように注ぎかける装置。また、その水や湯。
6	勤め先に出かけること。また、勤めに出ていること。
7	自分で自分の食事を作ること。
9	事務を取り扱う所。オフィス。
11	地面の下。
13	英語で「家」「建物」「小屋」などの意味を表す言葉。
15	利益を受ける権利。
16	他からの攻撃などに対し、自分の力で自分を守ること。

【懸賞クロスワードパズル！】