Master of Science Thesis

Brain-computer interface-based feedback to enhance motor rehabilitation

Stavrina Devetzoglou-Toliou

Supervisors
Dr. Ir. A.C. Schouten, Dr. J.J.S. Norton

NCAN National Center for Adaptive Neurotechnologies
TU Delft Delft University of Technology

Challenge the future 2020

Brain-computer interface-based feedback to enhance motor rehabilitation

by

Stavrina Devetzoglou-Toliou

to obtain the degree of Biomedical Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday August 19th, 2020 at 15:00 PM

Student number: 4741560

Thesis committee:			
	Dr. Ir. A.C. Schouten	Chairman BME	BME, TU Delft
	James J. S. Norton, Ph.D.	Daily Supervisor	NCAN, Albany, NY
	Jinne Geelen, Ph.D. Candidate	Internal Member	BME, TU Delft
	Dr. Ir. Daan M. Pool	External Member	AE, TU Delft
	Jonathan R. Wolpaw, M.D.	External Member	NCAN, Albany, NY

This thesis is confidential and cannot be made public until August 9, 2021.

TU Delft

Dedicated to Dr. Dennis J.McFarland
that I had the honor to meet

Abstract

The central nervous system (CNS) exhibits remarkable plasticity throughout life. The physiological changes in the CNS that occur due to plasticity allow us to perform new skills and old ones more effectively and efficiently over time.

Recently, it has been demonstrated that plasticity can be used to help people recover motor function after spinal cord injury (SCI), stroke, or other neurodegenerative diseases. Following injury or illness, neuronal pathways are disrupted, leading to exaggerated reflexes and motor impairments. Rehabilitation methods can help restore motor function by triggering beneficial plasticity (i.e., neuronal and/or synaptic changes that improve motor functions).

H-reflex operant conditioning that triggers beneficial plasticity is one promising new therapeutic approach to motor rehabilitation. In this paradigm, participants are operantly conditioned to change the size of abnormal reflexes associated with motor deficiencies (either increased or decreased as needed), which consequently improves movement. H-reflex operant conditioning has no known adverse side effects and it can complement other therapies. Two present limitations of H-reflex operant conditioning are its success rate and the length of time required to complete the conditioning.

Given that the beneficial plasticity induced by this paradigm is modeled to start in the sensorimotor cortex, we designed an enhanced H-reflex operant conditioning system that provides people with brain-computer interface (BCI)-based feedback on activity from this region of the brain. We hypothesize that by guiding this critical first stage of plasticity, it should be possible to enhance the efficacy and efficiency of this paradigm.

This thesis is organized as follows. Chapter 1 introduces the H-reflex operant conditioning and the logic for our enhanced H-reflex operant conditioning system. Chapters 2 and 3 describe experiments conducted to identify and train participants to use our BCI-based feedback system. Five participants completed the training; four of these participants learned to use the BCI with better than 70% accuracy and three of these four participants significantly improved their accuracy with training. Chapter 4 lays out the design of the enhanced H-reflex conditioning system. Finally, Chapter 5 presents plans for experiments to test the system when human-based research is able to safely resume following the global COVID-19 pandemic and potential directions of future work.

Acknowledgements

I feel blessed to have given the chance to meet a whole new world during my thesis project. I would like to express my sincere gratitude to Dr. Wolpaw for giving me that opportunity to expand my horizons, as well as my professor at TU/Delft Dr. Schouten and my supervisor Jinne Geelen. With the same gratitude, I would like to thank Dr. Norton for accepting me under his supervision and introduce me to his work. He and his amazing wife, Stephanie Dockins, gave me a warm welcome and I appreciate their amazing hospitality. Thank you for all the wonderful adventures we had exploring nature, food, and traditions.

I cannot express in words all my gratitude and happiness for having the chance to meet and work alongside Dr. McFarland, who helped me with the data analysis and explained complicated concepts. Together we took critical decisions for the development of my experiments. Unfortunately, he is no longer among us but I hope he will be able to see how grateful I am for being his last student.

Furthermore, I would like to thank from the bottom of my heart all the other members of the group, Theresa Vaughan, Susan Heckman, Jonathan Carp, Tim Fake, and Lynn McCane for being amazing colleagues and for welcoming me to their group. I would like to give special thanks to William Sarnacki for training me to perform SMR training and gave his valuable experience acquired from many years of experiments.

I would like to express my appreciation to Dr. Brunner for introducing me to his lab and helped me when I needed it. Special thanks to Jeremy Hill and Markus Adameck for their support on software issues and all amazing people for their feedback on my work, James Swift, Hohyun Cho, Tao Xie, Amin Nourmohammadi and everyone else in Brunner's lab, I thank you all!

Furthermore, I would like to thank my biggest fans: my mother, my father, and my brother for their unconditional support, care, love, and for always believing in me! My good friend Andrada Velea for all the support and help when I had to decide to accept this new challenge and all the wonderful memories in Delft and not only!

Last by not least, thank you Diane Ray and Claire Qu! Our amazing secretaries for taking care of all the organization of my essential documents. It was because of Diane bringing delicious sweets almost every day at work that I am heavier!

Contents

Abbreviations

BCI	Brain-computer interface
CNS	Central nervous system
CST	Corticospinal tract
CT	Control trials
ECR	Extensor carpi radialis
EEG	Electroencephalography
EMG	Electromyography
EPOCS	Evoked Potential Operant Conditioning System
ERD	Event-related desynchronization
ERS	Event-related synchronization
FCR	Flexor carpi radialis
GUI	Graphical user interface
MVC	Maximum voluntary contraction
NCAN	National Center for Adaptive Neurotechnologies
RC	Recruitment curve
SCI	Spinal cord injury
SMC	Sensorimotor cortex
SMR	Sensorimotor rhythm
ST	Stimulus test
TT	Training trials

List of Figures

List of Tables

1 Introduction

"Neuroplasticity is the ability of the brain to change its behavior as result of experience", Eric Kandel

The central nervous system (CNS) exhibits remarkable plasticity throughout life [19, 22]. Previous theories that plasticity only occurs during development have given way to the recognition that skill acquisition—from the simplest of skills to complex ones like dancing—induces plasticity in people of all ages. The neural mechanisms of this plasticity are beginning to be understood; skill acquisition first induces plasticity in the brain, which then guides and maintains plasticity in the spinal cord [41, 56, 63]. The physiological changes in the nervous system that occur with learning allow us to perform new skills more effectively and efficiently over time. They do not, however, disrupt our ability to perform previously-learned skills [52].

Recently, it has been demonstrated that plasticity can be used to help people recover motor function after spinal cord injury (SCI), stroke, or other neurodegenerative diseases [38, 47]. Following injury or illness, neuronal pathways are disrupted, leading to exaggerated reflexes and motor impairments [64]. Multiple rehabilitation methods have been developed that restore motor function (e.g., repetition of skills [23, 45], spinal cord stimulation [13], and H-reflex operant conditioning [47]) by triggering beneficial plasticity (i.e., neuronal and/or synaptic changes that improve motor functions).

H-reflex operant conditioning is a new approach for inducing beneficial plasticity. In this protocol, people learn to increase or decrease the size of their reflexes. This induces plasticity in specific neuronal pathways; and, in people with motor impairments, helps them recover function. H-reflex operant conditioning can be used exclusively or to complement current rehabilitation methods. Nevertheless, at present, H-reflex operant conditioning is successful in only $\sim$ 70% of people [47], and the protocol takes about three months to complete. In this thesis, we propose a novel addition to the existing protocol that is expected to increase its success rate and speed of reflex change and consequently improves the therapeutic benefit of the protocol for individuals with motor dysfunctions.

1.1. Background Information

1.1.1. H-reflex

The Hoffmann reflex (H-reflex), first described in 1910 by Paul Hoffmann [17], is an electrically induced analog of the spinal stretch reflex. When a weak electrical stimulus is delivered directly to the skin overlying the nerve, it can excite the large I_a afferent fibers within the mixed nerve (Figure 1.1). The stimulus heads to the spinal cord through the dorsal root and elicits action potentials that travel down the α-motoneuron. These action potentials elicit a synchronized muscle contraction that can be measured with EMG (i.e., the H-reflex) [37, 50]. In addition to the H-reflex response, the electric stimulation of the peripheral nerve causes a direct muscle response due to the direct activation of the α-motoneurons. This muscle response, preceding the H-reflex due to the shorter pathway length, is known as the M-wave.

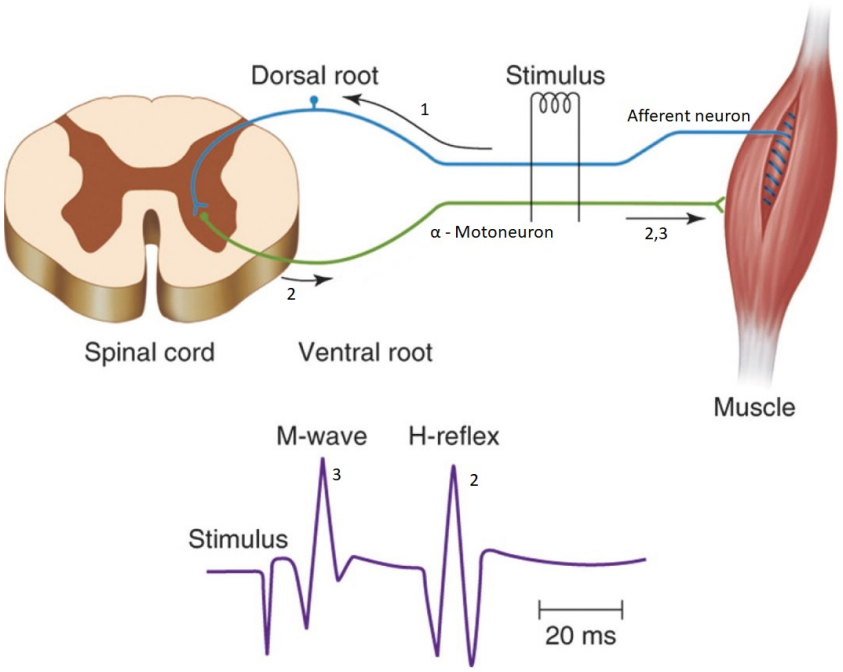


Figure 1.1: Electromyographic responses of the muscle after nerve stimulation. The nerve stimulation produces a direct muscle response or M-wave (response 3) and a spinally mediated H-reflex response (responses 1 and 2). The M-wave is quicker due to the shorter pathway that the induced potential must go through until it reaches a few large α-motoneuron axons. Meanwhile, the H-reflex response that follows is slower, occurring when the large proprioceptive afferent axons are excited. (Modified from Bamford and Davis [2])

Although the H-reflex comes from a monosynaptic path, many factors can affect its size. For example, ambient temperature, age, caffeine intake, time of the day, medication, and movement of another limb are all known to affect the H-reflex [15]. Furthermore, the elicitation of the H-reflex can be influenced by the level of muscle contraction at the time of stimulation [15]. In fact, some muscles can produce a measurable H-reflex only when they are active (like the brachioradialis), and others (like the flexor carpi radialis (FCR)) can be measured when the muscle is at rest [4, 65]. Therefore, when conducting experiments that use the H-reflex, it is crucial to assure that all these factors remain as stable as possible.

In motor control research, the H-reflex is an essential tool for assessing the nervous system's response [5]. This is due to the ease with which the H-reflex can be elicited and recorded noninvasively with percutaneous stimulation in various muscles throughout the body (e.g., muscles of the hand, arm, leg, foot, and jaw). Since pathways of the peripheral nervous system are more easily accessible than those in the brain, H-reflex measures are used to test for abnormalities of the CNS caused by injury or disease (e.g., stroke, SCI). H-reflex related research contributes to further understanding of motor dysfunction mechanisms observed after those incidents, as well as, provide valuable information for the design of new therapeutic methods or the improvement of the existing ones.

1.1.2. H-Reflex Operant Conditioning

H-reflex operant conditioning protocol is a promising new therapeutic method for motor function recovery. Through a series of sessions, people can gradually increase (up-conditioning) or decrease (down-conditioning) the size of their H-reflex depending on a rewards system. The reward is based on EMG response produced by a specific CNS pathway that is eventually changed.

Motor function improvement through the protocol, is attributed to plasticity induced in both the brain and the spinal cord. Brain plasticity starts in the sensorimotor cortex (SMC), where reflex pathways as part of the corticospinal tract (CST), originate. Multiple brain structures have been shown to be critical for spinal reflex conditioning. Ablation of the inferior olive, cerebellum, and SMC, all prevent reflex conditioning from occurring in animal models [8]. Based on these studies, the current hypothesis is that reward elicits activity in the inferior olive [11] that induces plasticity in the cerebellum [54], which

subsequently produces plasticity in SMC [10, 51, 56]. Through the brain's descending influence on the spinal cord, H-reflex operant conditioning also induces beneficial changes in spinal reflex pathways [6, 7, 9]. Consequently, multiple behaviors that use these pathways are improved by these changes. This wider plasticity reflects how pre-acquired behaviors using the same neural pathways, not only are not hindered by the change but can be enhanced if the change is valuable.

Therefore, the H-reflex operant conditioning is a targeted method designed to address specific functional deficits according to each individual's needs. It can serve as a therapeutic approach for those with SCIs, brain injuries, stroke, peripheral nerve injuries, or other chronic neuromuscular disorders [12, 46]. Those people often experience decreased control of their limbs. Exaggerated reflexes are identified to their impaired limbs and contribute to spasticity, contractures, and other conditions that prevent them from performing smooth fluid movements.

The first study of the H-reflex operant conditioning on 13 SCI patients was conducted in 2013 by Thompson et al. [47] with promising results. Patients underwent a down-conditioning of the soleus muscle H-reflex of their impaired leg, leading to increased walking speed, improved limping, and more symmetrical locomotion pattern. The widespread beneficial plasticity contributed to overall motor ability, more specifically, improvement of the locomotive function for both of their legs [47]. Hence, altogether, the emerging picture is that the H-reflex operant conditioning is a method that can target specific spinal pathways. It can strengthen or weaken H-reflexes as needed, to improve motor function and simultaneously trigger more extensive beneficial plasticity.

Conditioning Protocol

The standard protocol consists of at least 30 1-hour sessions—six baseline sessions, 24 conditioning sessions, and four follow-up sessions optionally (Figure 1.2). Human conditioning session rate is at least three sessions per week for 8-10 weeks.

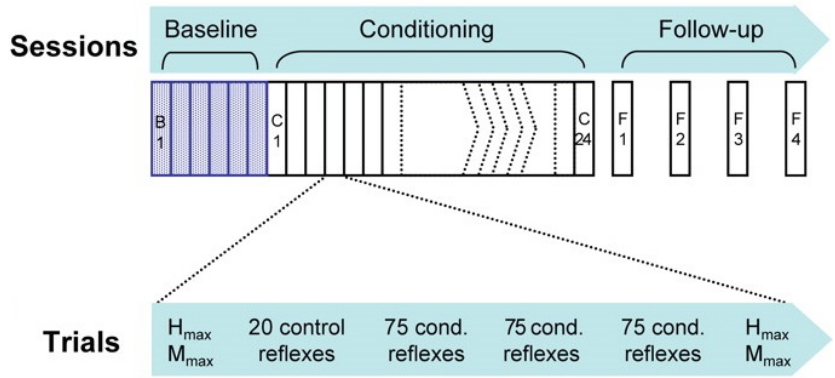


Figure 1.2: The H-reflex operant conditioning protocol consists of baseline, conditioning and follow-up sessions. The baseline sessions include 20 control trials, and 225 more control trials and participants do not receive H-reflex feedback. The conditioning sessions have 20 control trials prior to 225 conditioning trials in three blocks of 75 trials, where participants try to increase or decrease their H-reflex size. They are given feedback on their H-reflex after every conditioning trial. The follow-up sessions contain control trials and are performed within three months after the end of the conditioning sessions. (From Thompson et al. [46])

The baseline sessions consist of 245 trials where participants are asked to maintain a stable amount of background EMG activity and, then a stimulation occurs. The H-reflex is simply elicited without participants trying to change it and receiving feedback as to H-reflex size.

During the conditioning sessions, participants are given additional instructions to change their H-reflex size in a predefined direction (up or down-conditioning). Each conditioning session consists of a sequence of 20 control and 225 conditioning trails, and after each trial, participants are given visual feedback on the size of their H-reflex. Participants are asked to maintain a certain level of background muscle activity for a specified period for an H-reflex to be elicited from the stimulation of the corresponding nerve (e.g., the median nerve for the FCR muscle). The stimulation level, reflected

by the M-wave size, is kept constant within and across sessions. Reward follows directly after the H-reflex; a positive reward comes when H-reflex size follows a desired direction, and it is larger or smaller than a predefined criterion value [16, 46, 58]. It is desirable for the participant to hold a stable posture and joint angles throughout the session. Varying positioning between sessions impedes the learning process and affects H-reflex measures, as mentioned before.

The follow-up sessions resemble the baseline sessions, but they are performed 15 days, one month, two months, and three months after the conditioning sessions have ended. During those sessions, the persistence of the changes due to the protocol is assessed.

It is safe to perform the H-reflex operant conditioning protocol to healthy individuals and people with motor deficits since there are no known side effects. In the former group of people, changes caused by the protocol disappear within three months [46], as their neural system returns to the previous equilibrium state. In contrast, for the latter, results persist and lead to the improvement of specific motor functions.

Phases of H-reflex Conditioning

H-reflex operant conditioning plasticity occurring in the CNS is reflected by two distinct phases: the first, the task-dependent adaptation, and the second, the long-term change [55] (Figure 1.3).

The two phases are thought to primarily reflect plasticity in the brain and spinal cord, respectively. The first is a change in the H-reflex in the correct direction that appears after the first four conditioning sessions in humans (1000 conditioning trials) [46, 55], and remains stable in magnitude [46] for the rest of the conditioning. Participants can turn it on and off at will (i.e., it is present only when the participants decide to change their reflex). It is thought to correspond to changes in the CST that is operantly conditioned by the reward contingency [46].

The second phase, the long-term change, starts later (after 10-12 sessions or 2500 trials in humans) and grows gradually over weeks. After its appearance, it is always present, and it is thought to reflect the spinal cord plasticity that is gradually created from the first component [46].

Recent evidence suggests that changes in the SMC are involved in both phases of plasticity. Boulay, Chen, and Wolpaw [3] demonstrated that there was a correlation between activity in the SMC at specific frequency bands and the size of the H-reflex. Specifically, they show that an increased H-reflex was associated with an increase in SMC activity in the 5 – 30 Hz range and a decrease in activity at 100 – 200 Hz. This study opens the possibility that learning to change brain rhythms over the SMC may be used to modulate H-reflex amplitude.

Limitations

The expected success rate of the protocol is approximately 80% in healthy individuals; they change the size of their H-reflex in the desired direction [47]. The remaining 20% are not able to change the H-reflex size, with the explanation remaining unclear and requiring further investigation. The investigator's skills to execute the protocol correctly could be one possible explanation (e.g., when the investigator's expertise in administering the protocol improves, the success rate exceeds 80% [14, 60]).

In clinical settings, the success rate of H-reflex operant conditioning may be slightly lower. Presently, the success rate of the protocol in non-healthy individuals is approximately 70% [47]. In addition, the protocol is time-consuming. It consists of 30 1-hour sessions that are required for the completion of the method.

1.1.3. Sensorimotor Rhythms and H-reflex

In humans, SMRs are mu (8-12 Hz), beta (18-26 Hz), or gamma (>30 Hz) frequency band oscillations recorded over the SMC [33]. When recording with electroencephalography (EEG), mu and beta are more prominent, and they reflect activity in the SMC related to movement. SMR amplitude decreases during active movements and increases during the absence of motion [29, 36]. The former is known as event-related desynchronization (ERD), and it is interwoven with cortical networks being activated, while the latter is known as event-related synchronization (ERS) when cortical networks are deactivated or inhibited [28, 30, 31, 34].

There is evidence that patterns of cortical activation during movement are similar to the ones identified during the imagination of movement (motor imagery) [32]. Figure 1.4 shows ERD and ERS patterns obtained during actual and imagined movement of the hand using EEG. The similarities between the two topographical maps suggest that the same cortical structures are involved. ERD and ERS for foot

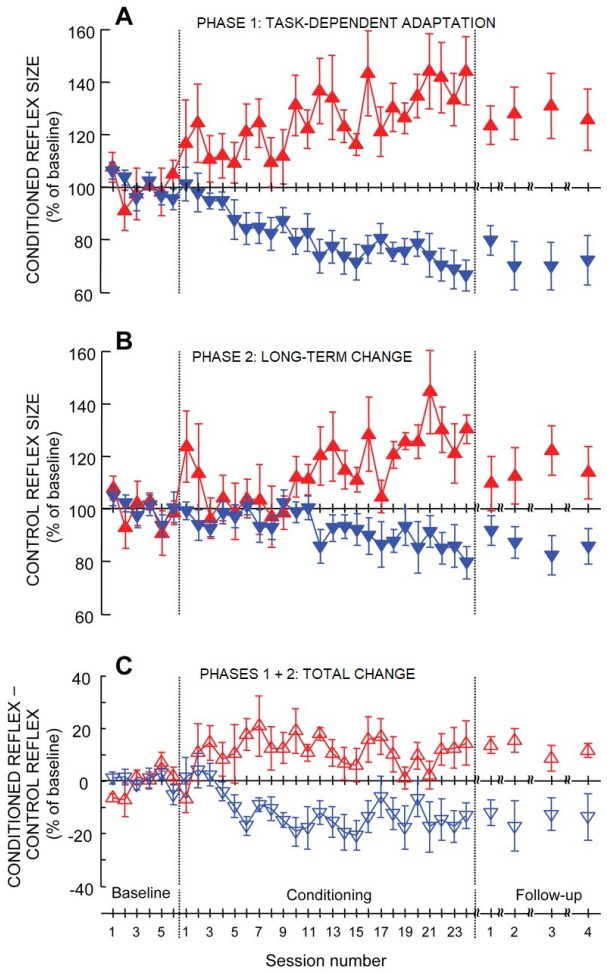


Figure 1.3: (Task-dependent adaptation (phase 1), long-term change (phase 2) of the H-reflex operant conditioning, and their sum (Phase 1+2). The up triangles (red) represent up-conditioning and the down triangles (blue) down-conditioning. The values of the plots are average (±SE) for baseline, conditioning, and follow-up sessions. The top plot shows the H-reflex change (increase or decrease) that happened after the first four conditioning sessions. This change is controlled by the participant as they can turn it on or off at will. The middle plot shows the average H-reflex sizes gathered from the 20 control trials that are performed at the beginning of every session, depicting the long-term change due to spinal plasticity. The last plot is the sum of the two previous plots showing the total effect of the H-reflex operant conditioning protocol on the H-reflex size of the participants. (From Thompson et al. [46])

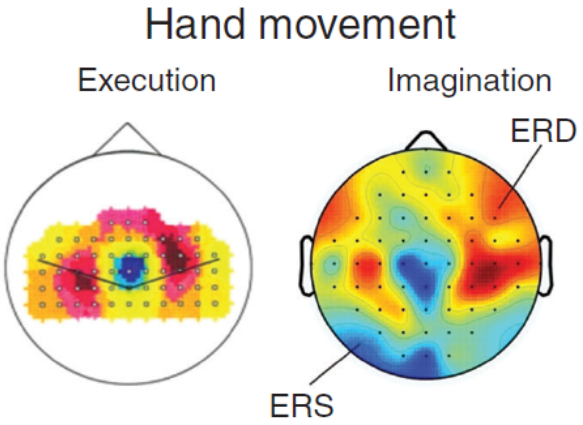


Figure 1.4: Topographic maps displaying ERD and ERS of the hand during actual and imagined movement of the hand using EEG. The focus is on depicting the similarities of ERD and ERS appearance between execution and imagination (i.e., the spatial distribution patterns) and not the exact values of neural activity. (Modified from Pfurtscheller and Neuper [35])

and hand movement can be detected mainly over the SMC as a localized event. Thus, cortical activation associated with movement execution or movement imagination is reflected by the decrease in mu/beta rhythms.

Research has shown that people can learn to regulate their SMRs [59, 61, 62], through a series of sessions, a procedure that we call SMR training. In other words, they learn to increase or decrease their EEG amplitude voluntarily when alternating between rest state and motor imagery state (Figure 1.5). Most people initially use motor imagery to help them synchronize or desynchronize their SMR. This, however, is not necessary as many different strategies have been reported [59]. When the SMR modulation becomes like a regular muscle-based action, no specific strategy is needed.

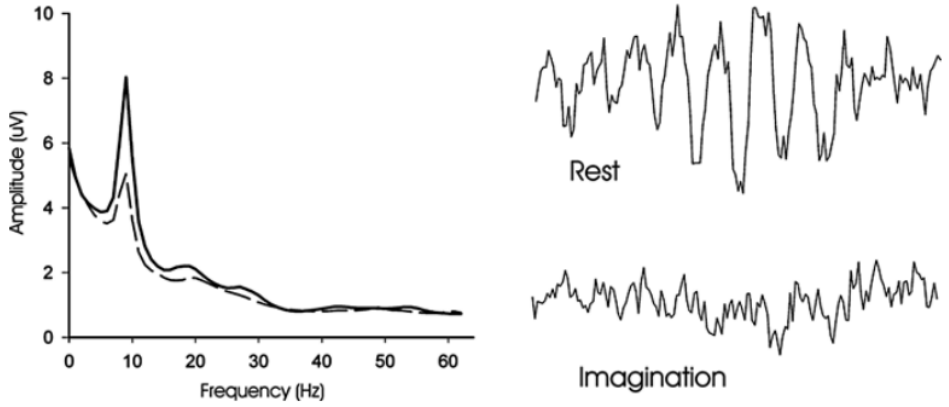


Figure 1.5: The change of SMRs during imagery and rest. Left: Frequency spectra recorded over the SMC with EEG. The solid line corresponds to the resting state, and the dashed line was recorded during the imagination of the right-hand movement. Around 10 Hz, there is a peak that is more prominent during rest. Right: 1-second segments of EEG from the same person during rest and imagination, with 10 Hz being prominent at the rest segment. (From Sellers et al. [42])

In this thesis, an SMR-based BCI is used for the SMR training of the participants [57]. A BCI is an intermediate system that translates brain signals into specific control signals that can control other devices. Specifically, during the SMR training, when SMR amplitude changes are detected from the BCI system, they can be translated appropriately to move a cursor on a screen.

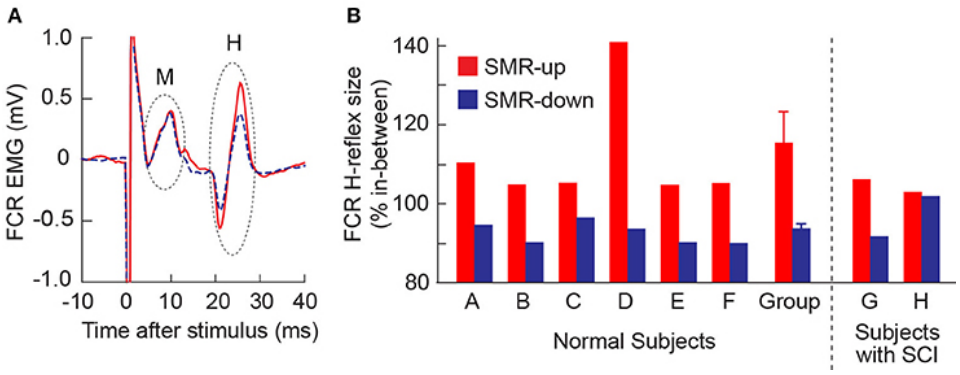


Figure 1.6: SMR modulation after SMR training affecting the size of the H-reflex. (A) Averaged EMG response of the FCR during increased SMR (red) and decreased SMR (blue) from participant D. (B) Averaged FCR H-reflex sizes for all the participants of the study (A-F: normal participants and G-H: SCI participants). The red bars correspond to SMR-up trials (increasing the SMR) and blue to SMR-down (decreasing the SMR). The group averages of the H-reflexes can be found with 116 ± 6 (mean ± SE) % for SMR-up and 92 ± 1% for SMR-down trials. (From Thompson et al. [48])

Recently, Thompson et al. [48] showed that learning to modulate SMR affects the size of the H-reflex [48]. When SMR synchronization is high, H-reflexes are larger in amplitude, and when SMR desynchronization, H-reflexes are smaller in amplitude (Figure 1.6). Even more interestingly, the study showed that the size of the H-reflex change measured during the experiment, was comparable to the magnitude of the task-dependent adaptation component of the H-reflex change during the H-reflex operant conditioning.

Based on Thompson et al. study [15], SMRs seem a promising addition to the H-reflex operant conditioning as it may bring encouraging results for its success rate and efficacy. Even more, the two components of the H-reflex operant conditioning might be able to be enhanced, leading to more rapid, and augmented magnitude desired H-reflex changes. All the above might contribute to rendering H-reflex operant conditioning an efficient and practical clinical rehabilitation method in the future.

1.2. Objective

This thesis describes a new approach to enhance the effectiveness of the current H-reflex operant conditioning protocols. This approach is based on the incorporation of BCI-based feedback during H-reflex operant conditioning.

1.3. Approach

Enhanced H-reflex Operant Conditioning

The enhanced H-reflex operant conditioning is the first attempt to combine SMRs with H-reflex operant conditioning. The new protocol is similar to the H-reflex operant conditioning protocol described earlier with the addition of SMR feedback provided to the user. Following the methods used in the study Thompson et al. [48], participants will be trained to modulate their SMR first. Furthermore, the additional SMR feedback that participants will receive during the new protocol should be analog to the one they were receiving during the SMR training. Lastly, they will undergo through the enhanced H-reflex operant conditioning.

For this accomplishment, essential modifications needed to be incorporated into the existing H-reflex operant conditioning protocol but also at the system used (hardware and software). In this study, we mainly focus on the software component of the system as the hardware needs to meet the previous needs plus EEG recordings. A more detailed description is given in Chapter 4.

The enhanced operant conditioning protocol attempts to combine two different protocols, the SMR training and the traditional H-reflex operant conditioning, with the prospect of a potential increase in the magnitude, speed, and reliability of H-reflex change. Furthermore, the outcome of this combination is expected to contribute to H-reflex operant conditioning, becoming a complement method to existing rehabilitation methods for patients with movement deficits such as SCI patients, stroke patients, or people suffering from other neurodegenerative diseases.

1.4. Specific Aims

The objective of this thesis has been broken down into specific aims.

1. H-reflex and SMR screening to identify individuals with a measurable H-reflex and SMR (Chapter 2)

   The H-reflex screening was performed with EPOCS to identify if participants have a measurable H-reflex. Only participants with an identifiable H-reflex can proceed to the experiment with the SMR screening. Restrictions are imposed due to H-reflex operant conditioning that requires the elicitation and the measure of the H-reflex from the targeted muscle. The SMR screening provides useful data for calibration of the system used for SMR training.

2. Perform SMR training to teach participants how to modulate their SMR (Chapter 3)

   The training was accomplished through a closed-loop real-time Brain-Computer Interface (BCI). EEG signals were gathered and were given to the BCI system as input. After internal signal processing, the brain signals are translated into feedback through cursor movement on a screen. Participants were able to influence the cursor's trajectory that depends on the received brain signals amplitude.

3. Develop an updated version of EPOCS for H-reflex operant conditioning to perform the enhanced H-reflex operant conditioning (Chapter 4)

   Software: Python and C++ programming was required to incorporate the translated brain signals to appropriate visual feedback incorporated into the existing GUI of EPOCS. Hardware: EEG acquisition hardware was added to the existing setup.

Basic principles of the H-reflex operant conditioning protocol are kept the same (e.g., number of sessions, but SMR feedback is provided to the participants). Specific requirements of the SMR feedback should be met for a stimulation to happen. The data analysis would be performed with MATLAB. A comparison of the participants progress between the H-reflex operant conditioning and the enhanced H-reflex operant conditioning was expected.

1.5. COVID related plan changes

The initial goal of this study was to assess the effect of SMRs modulation on the H-reflex operant conditioning protocol, as SMRs are expected to increase the efficacy of the protocol. After SMR training, participants would follow the H-reflex operant conditioning protocol enhanced by SMR feedback (i.e., the enhanced H-reflex operant conditioning).

Specific aims 1-3 were accomplished. Due to the COVID-19 outbreak, the enhanced H-reflex operant conditioning, component of specific aim 3, was postponed. Therefore, this thesis describes the experimental protocols, data, and analyses that were completed prior to the shutdown.

2

Screenings

The conduction of the enhanced H-reflex operant conditioning requires a measurable H-reflex from the participants. To examine the compliance of our participants according to this requirement, we performed the H-reflex screening. The participants who completed the H-reflex screening proceeded to the SMR screening, which provides the potentially initial features to be used for the SMR training. More details about the meaning of the initial SMR features can be found under section 2.2.

2.1. H-reflex Screening

The H-reflex screening assessed whether we could elicit a measurable H-reflex from each participant using our experimental setup. This screening was essential because participants with a non-detectable H-reflex cannot change their H-reflex size through the H-reflex operant conditioning method as it is currently designed. The screening could take up to three sessions and each session was approximately one hour and 15 minutes. After the three sessions, if no visible H-reflex had been detected, the respective participant was excluded from the study. In contrast, when an H-reflex was detected, the participant was considered eligible.

2.1.1. Method

Participants

Nine participants (three males, six females, 21–70 years old) participated in this study. Individuals were excluded from participating if they had a history of neurological or chronic illness. Participants were compensated with $20 per hour for their time. The experiments were approved by the Institutional Review Board at the New York State Department of Health's Wadsworth Center (IRB#05-058) and were performed at the David Axelrod Institute in Albany, NY.

Experimental Setup

The National Center for Adaptive Neurotechnologies (NCAN) has developed a complete system—including both hardware and software—for the conduction of H-reflex operant conditioning protocols, the EPOCS. The software component of EPOCS is general-purpose; it can be configured differently, depending on the needs of the protocols, to use many different types of hardware for reflex conditioning. Here, we describe the setup of EPOCS as it was used in this thesis for all the H-reflex screening data collection from the FCR muscle (Figure 2.1).

Hardware

The hardware component of EPOCS is composed of four main parts: a stimulator, a biosignal (EMG) amplifier, an analog to digital converter (DAQ), and a computer. In our experiments, we elicited H-reflexes from the FCR muscle using transcutaneous stimulation (DigiTimer DS8R, DigiTimer, UK) of the median nerve and measured them using EMG (Bortec AMT-8; Bortec Biomedical Ltd., Canada). All of the EMG signals were digitized using a National Instruments USB data acquisition system (NI USB-6212; National Instruments, Austin, TX). Real-time data processing was performed on a Dell

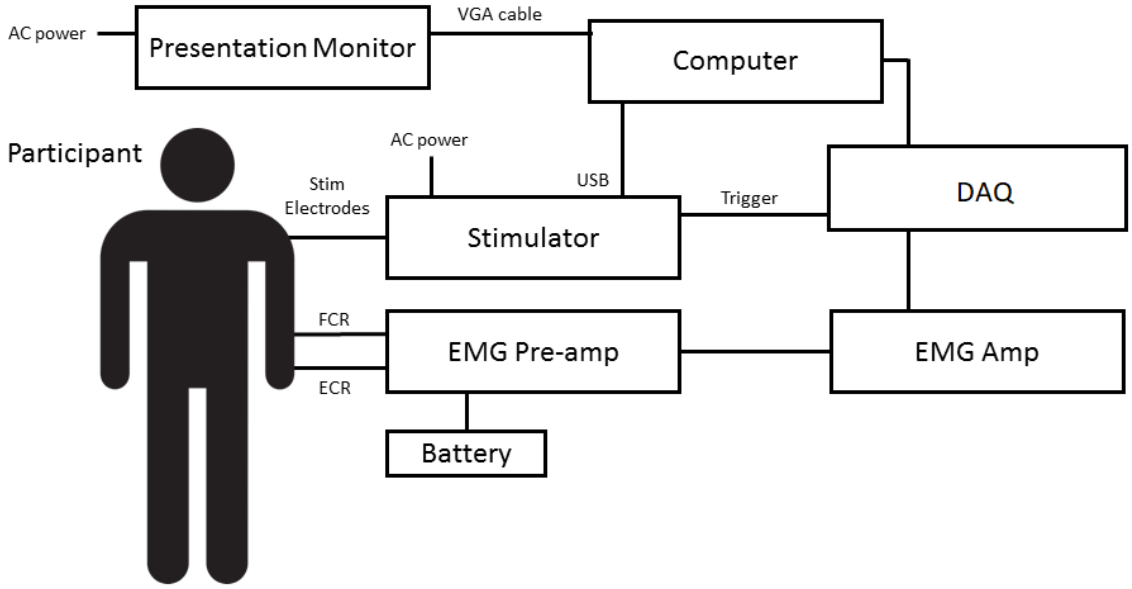


Figure 2.1: The diagram of the system used for H-reflex screening. The participant is sitting in front of a presentation monitor that is connected to the computer running EPOCS. The computer receives information from the DAQ, which receives data from the EMG amplifier. The gathered data reaching the EMG amplifier are the EMG data collected form the EMG pre-amplifier, which is connected with the electrode pads on the arm of the participant over the agonist and the antagonist muscles. The stimulator is connected from one side to the stimulation electrode pads, the anode and the cathode, over the median nerve of the participant, and on the other with the DAQ and the computer via USB. When certain conditions are met, a signal is sent from the computer to the stimulator to fire a trigger.

computer (Dell Technologies Inc., Round Rock, TX), and feedback was provided to the participants using a monitor (LG Electronics Inc, South Korea).

EPOCS has both a trigger output channel and a trigger input channel. When EPOCS triggers a trial, it outputs an 80-ms 5 V square-wave pulse on its trigger output channel, which is connected to the stimulator. Concurrently, EPOCS is detecting and analyzing epochs of EMG signal time-locked to rising edges that it detects on its trigger input channel. According to the current configuration, the gap between the last sample of EMG that influences the triggering decision, and the first sample on which the trigger is detected, is 2–3 ms, with a variance of less than 1 ms. By default, EPOCS triggering decisions are dependent on the EMG amplitude being held within a certain range for a specified period.

Software

The software component of EPOCS was installed on a PC running Windows 7 (Microsoft Corporation, Redmond, WA). The software stores user-specific variables (e.g., participant number, stimulator settings, etc.) and provides an easy-to-use graphical user interface (GUI) for the experimenter and participant. Presently, it includes experimenter and participant GUIs for five different types of data collected during evoked potential operant conditioning protocols—stimulus test (ST), maximum voluntary contraction (MVC), recruitment curve (RC), control trials (CT), training trials (TT). They are referred in this thesis as modes and used for specified tasks during the current protocol.

- **Stimulus Test (ST)**: Single pulses of electrical stimulation. They are applied to the nerve of the targeted muscle to test the response of the system with respect to the electrode pad placement before every session and during the H-reflex screening.

- **Maximum Voluntary Contraction (MVC)measurement**: Absolute EMG amplitude of the targeted muscle in maximum isometric contraction. The MVC measurements are used to adjust the muscle activity range (mV) that is appropriate according to each individual's specific abilities (Figure 2.2).

- **Recruitment Curve (RC)**: A mapping from the stimulation current to M-wave and H-reflex size. The RC is used to find a control point (i.e., the amount of current used for the beginning of the training sessions). A full H-reflex and M-wave RC of the target muscle that can be obtained by gradually increasing the stimulus intensity from zero to an intensity that would elicit the maximum amplitude of the M-wave. During an RC, participants maintain a certain level of EMG activity in a sitting position (Figure 2.3).
- **Control Trial (CC)**: The mode used for control sessions of the H-reflex operant conditioning protocol. When EMG activity remains within the specified range for at least two seconds, a stimulation is triggered to elicit and H-reflex (Figure 2.4).
- **Training Trial (TT)**: The mode used during the conditioning sessions. The operator asks participants to change the size of their H-reflex. During those sessions, visual feedback of the H-reflex size is given to participants in a separate bar called “Response” (Figure 2.5).

The modes that were used for the H-reflex screening were the ST, the MVC, and sometimes the RC.

Experimental Procedure

Before the H-reflex screening, each participant was informed about the study and signed an informed consent. Afterward, participants completed three questionnaires—a demographic and health history, the Edinburgh handedness inventory, and a survey on their activities (see Appendix A). To make our participants feel comfortable, a short lab tour was given, and they had the opportunity to learn more about the lab in general. At all times during the screening, participants were encouraged to ask questions about the current task and the overall study.

A detailed description of the task they would perform during the screening was explained as they took their seat on the chair inside the H-reflex lab (Figure 2.6). Participants were asked to sit with their back straight against the back of the chair. The desired position of the right arm during the H-reflex screening (as well as for enhanced H-reflex conditioning) was: shoulder flexed at 90°, elbow, forearm, and wrist in a neutral position (0°). The participants rested their arm on the right side table of the experimental chair so that their palm met the hand peg. To ensure that each participant was in a similar position, the chair was designed to be adjustable. Once the participant was comfortable, the experimenters made the necessary adjustments of the height of the table and the proximity of the table to the chair, as well as of the hand peg concerning the participants’ hand. The specific settings of the chair for each person were saved by measuring distances from stable points of the table-chair setup. This allowed us to consistently re-position the chair for each participant for future sessions. Afterward, their forearm was cleaned with rubbing alcohol to remove any excess skin oils, which contributes to more efficient conduction of the electrodes used for stimulation and measurement of EMG activity.

The next step was placing the electrode pads used for stimulation and the measurement of EMG activity. Initially, during the first electrode placement, the stimulation electrodes should be placed near the cubital fossa, the electrodes for muscle activity on the belly of the FCR muscle and its antagonist extensor carpi radialis (ECR) muscle, the ground on the stylus process of the radius and the reference electrodes on the tendon of the FCR muscle (Figure 2.7). For the identification of the FCR muscle and the ECR, participants were asked to perform some physiology assessments, according to the book Muscles Testing and Function [20]. Susan Heckman, the occupational therapist of our lab, evaluated the results. The stimulation electrodes were placed on the cubital fossa, but their placement changed throughout the screening to approximate the median nerve’s location based on the results of the EMG signal received. The table’s adjustments preceded the electrode pad placement as the arm’s position is critical for the correct muscle identification under the skin and pad placement on the skin. After determining the initial locations of the electrodes, standard 2.2 by 2.2 cm self-adhesive electrode pads (Vermed, A Nissha Company, Buffalo, NY) were placed on the participants’ right arm.

Screening

Participants were required to maintain a certain range of muscle activation throughout the screening. Weak isometric voluntary contractions potentiate H-reflexes [4], making them easier to elicit. Therefore, after electrode pad placement and attachment of the electrodes to the pads, we determined this range for each participant. This range is calculated through the MVC mode of the EPOCS software.

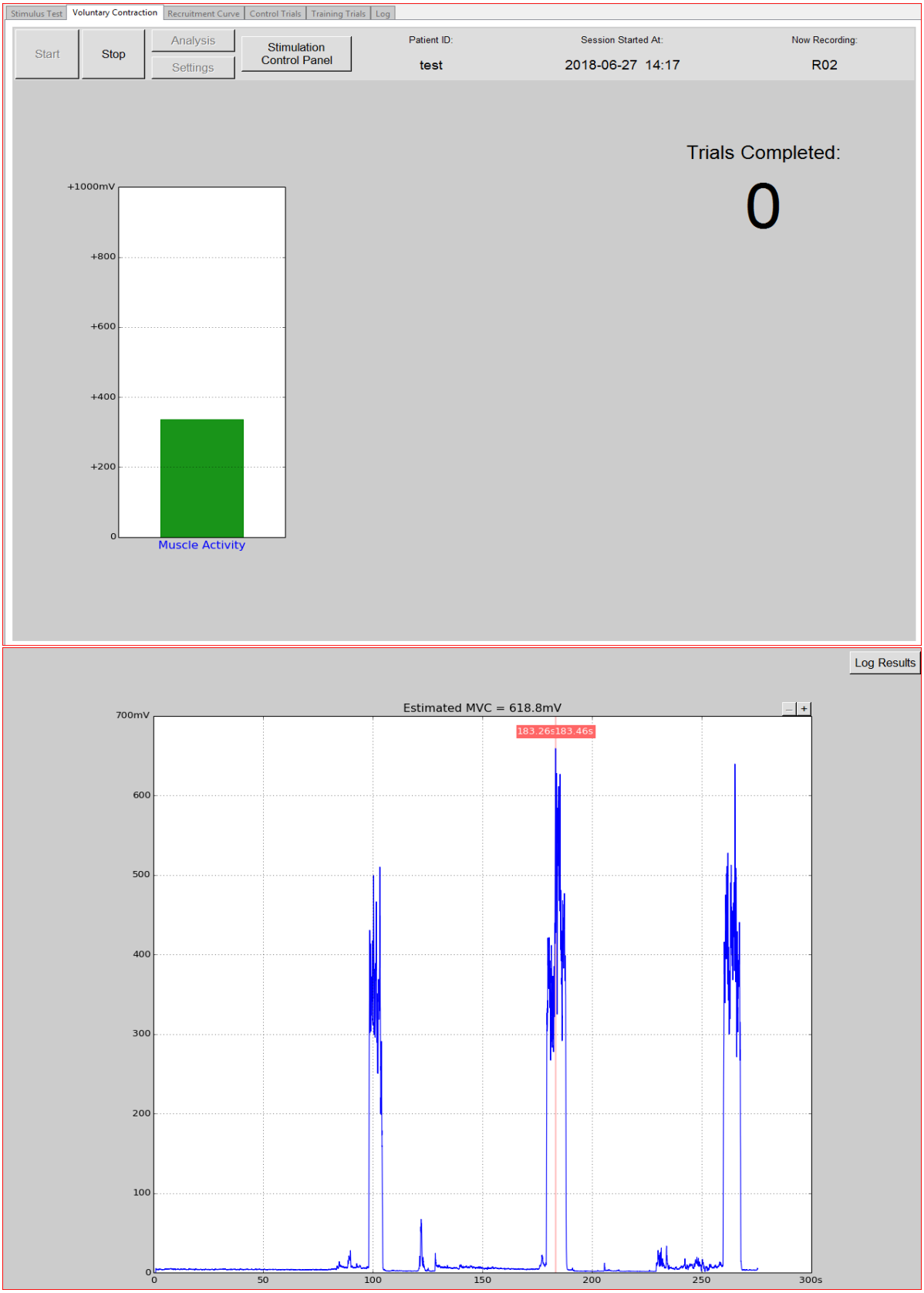


Figure 2.2: MVC mode of EPOCS. Up: GUI, as seen by the participant during MVC mode. The bar shows the magnitude of the muscle activation in real-time. Participants are asked to exert maximum muscle activation by flexing their wrist. This is repeated three times with a one-minute break in between. Down: Window showing the results after the MVC procedure has finished. The average values of the three MVCs are given by the software and are used from the operator for the calculation of the muscle activation limits during the protocol.

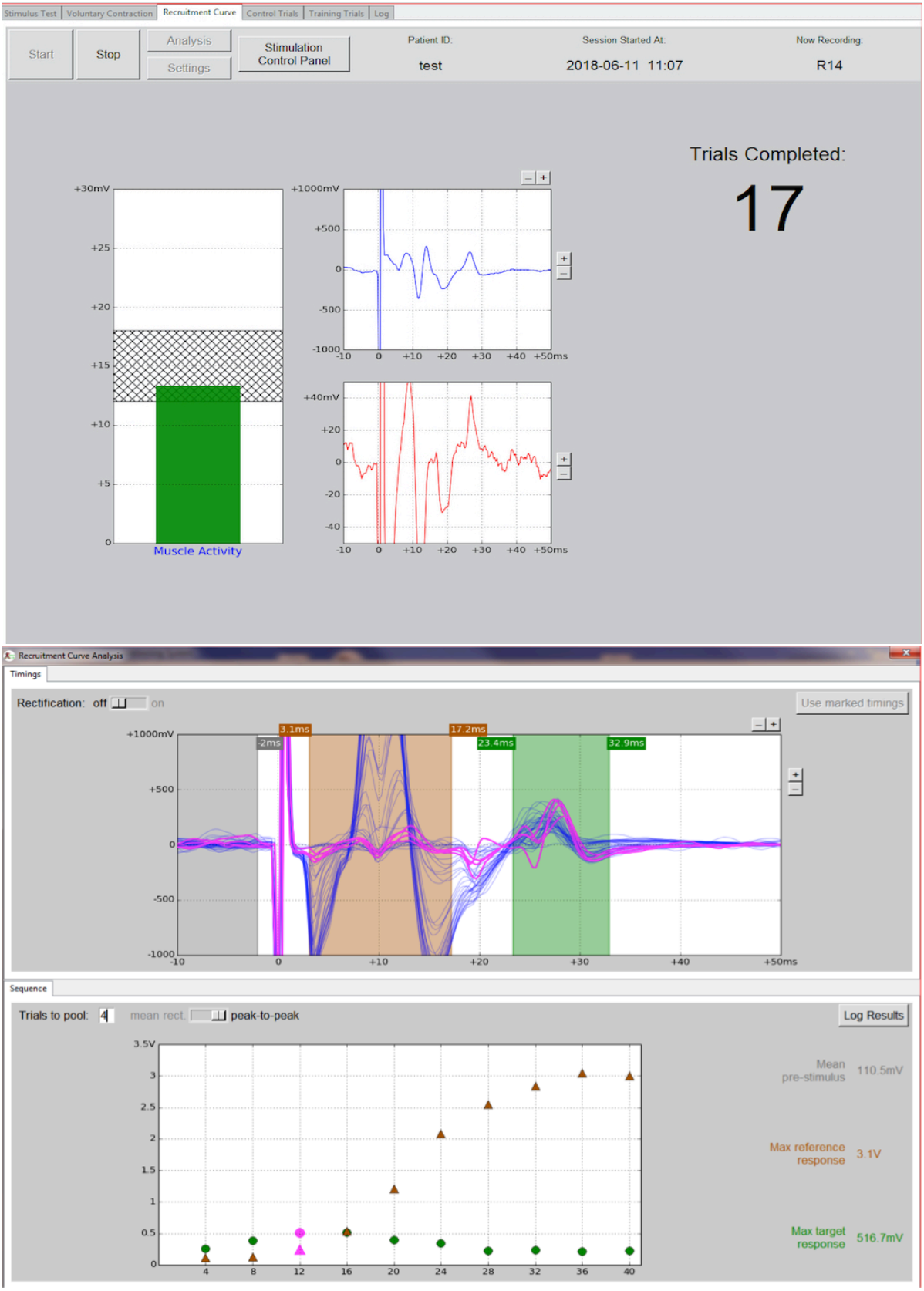


Figure 2.3: RC mode of EPOCS. Up: GUI, as seen by the participant during the RC mode. The bar on the left shows the current muscle activation recorded from EMG. The shaded area is the desired level of activation that needs to be maintained for a stimulation to be triggered. When the bar is within the shaded region, it turns green, indicating that this is the expected muscle activation level. In contrast, when the muscle activity is lower or higher than the shaded area, the bar turns red, indicating the opposite. The two windows next to the bar show the raw EMG signal obtained from the muscle to be conditioned (upper window) and the antagonist muscle (lower window). The trials performed are given on the right upper side of the window. Down: Analysis provided by EPOCS software right after the end of the RC. The top half shows all the recorded EMG signals obtained during the RC with the orange region identifying the M-wave limits and the green representing the H-reflex limits. The lower half shows the M-wave and the H-reflex size according to the limit areas that were selected on top.

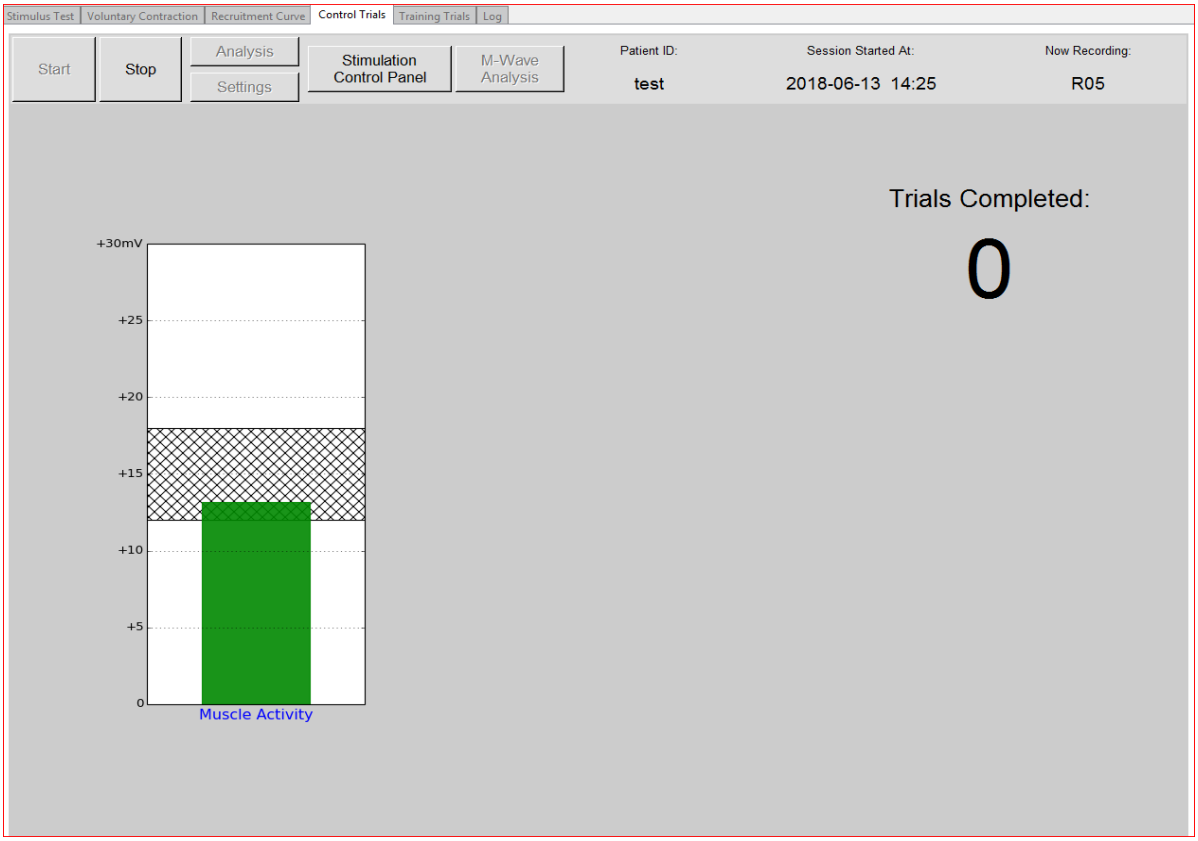


Figure 2.4: Control trial mode in EPOCS. The bar shows the muscle activation recorded with EMG form the targeted muscle. When the bar remains in the shaded area for more than two seconds, an H-reflex of the targeted is elicited by the stimulation of the corresponding nerve. The completed trials (top right) are updated after each trial. Participants are not able to see the size of the H-reflex that is elicited in every trial.

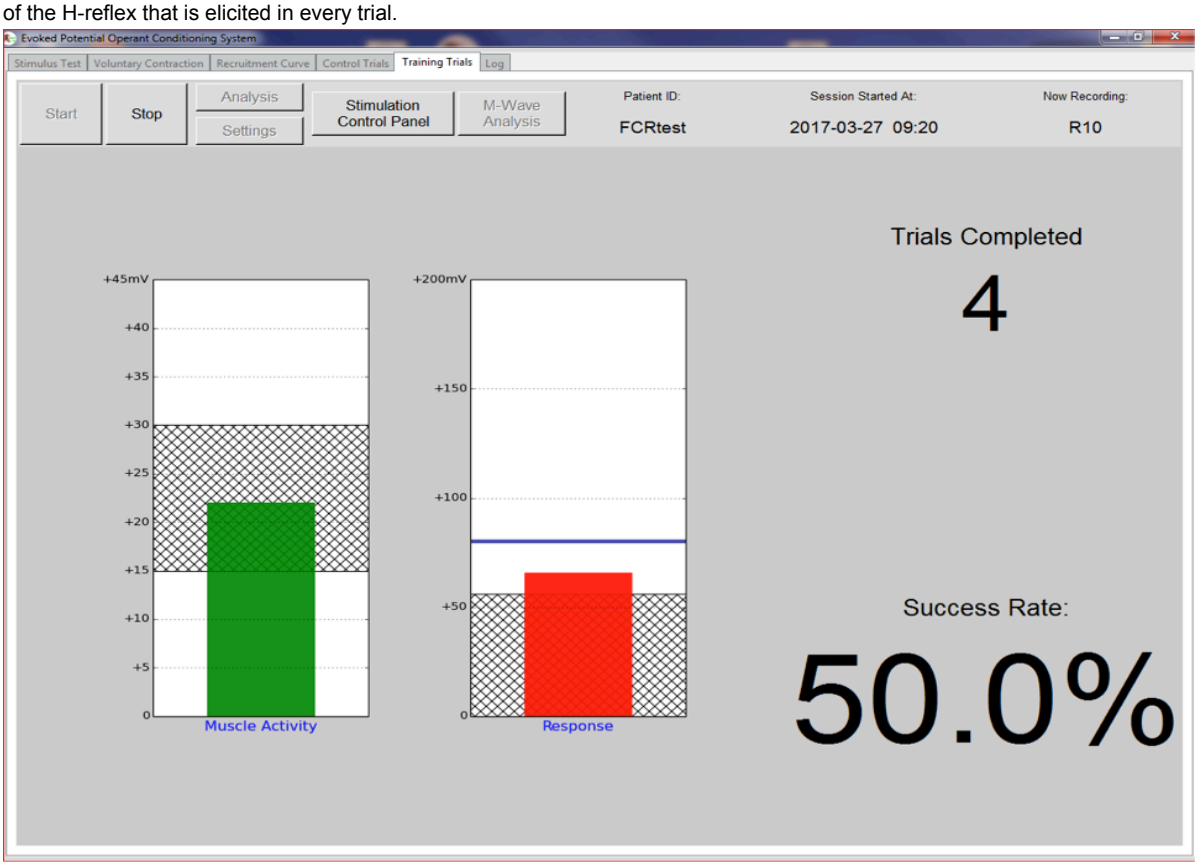


Figure 2.5: Training trial mode in EPOCS. The left bar shows the muscle activation recorded with EMG form the muscle that is conditioned. When the muscle activation bar is within the shaded area (desired limits of muscle activity computed from MVC), it turns green. If it is higher or lower than that range, the bar is red, and no stimulation is elicited. When the bar remains in the shaded area for three seconds, the stimulation of the corresponding nerve occurs, eliciting an H-reflex. The size of that H-reflex can be seen right after the stimulation on the right bar. If the size is within the desired range, the bar turns green, giving positive feedback to the participant. The solid black horizontal line represents the average H-reflex size recorded during baseline trials. The completed trials (top right) and the success rate (bottom right) are updated after each trial.

Figure 2.6: The chair and side tables used for the H-reflex screening. This setup is especially designed according to the needs of the H-reflex operant conditioning protocol. In other words, the height and the proximity of the side tables to the chair as well as, the hand peg are adjustable, so that the same setup can be used by multiple individuals.

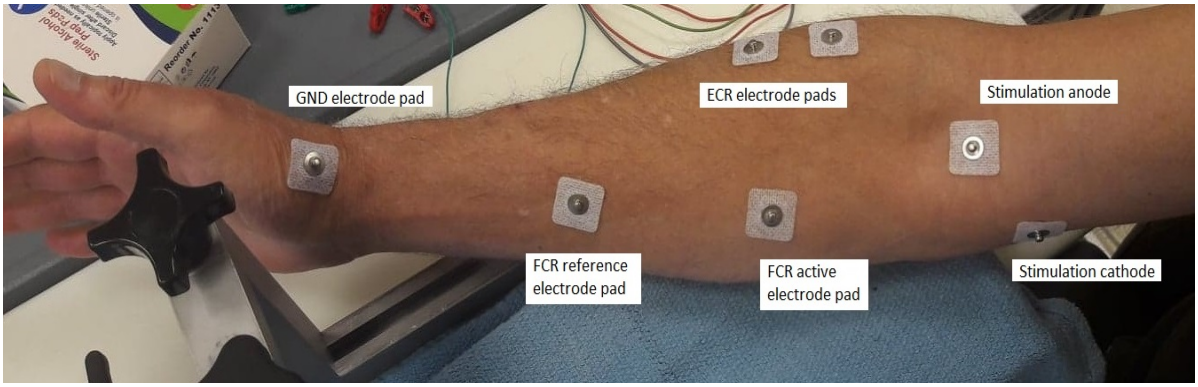


Figure 2.7: Electrode pad positions used during the H-reflex screening. The electrodes that were used from left to right are: the ground (GND) electrode pad on the bony structure of the wrist, one electrode used as reference ideally on the distal tendon of the FCR muscle, one FCR electrode pad placed on the belly of FCR measuring the activity of the muscle, two electrodes on the ECR muscle to measure muscle activity of the antagonism muscle and finally two stimulation electrodes, the anode and the cathode, for the median nerve stimulation.

Participants were asked to exert the maximum isometric contraction of the FCR muscle three times lasting five seconds each separated by one minute rest. During that procedure, participants were verbally encouraged by the operator to exert their maximum force. The lower limit and the upper limit of the muscle activation range were calculated as the 5% and the 10%, respectively, of the mean EMG amplitude of the three contractions.

Participants were asked to maintain their FCR muscle activation within the predefined muscle activation range for at least three seconds to elicit a stimulation. To help them to do this we provided visual feedback on their present muscle activation. After participants indicated they were ready, the experimenter slowly increased the stimulation current. After each stimulation, the experimenter visually inspected the EMG signals provided by the EPOCS software. If an H-reflex was not visible, then the operator could either increase the current or decide to change the position of the electrode pads used to stimulate the median nerve. This process was repeated for up to one hour or until an H-reflex was detected. If an H-reflex was detected, the locations of the electrodes were recorded so that they could be used again during the enhanced H-reflex operant conditioning protocol. If no H-reflex was detected, the participant was asked to come back for up to three sessions. If no H-reflex was detected after three sessions, the participant was determined to be ineligible to participate in the rest of the study. The H-reflex of each participant was identified by the experimenters through visual inspection of the EMG data using EPOCS.

2.1.2. Results

Seven out of the nine participants had a measurable H-Reflex (Table 2.1).

Participant	Gender	Age	Previous Training	H-Reflex	Continued
FCRS1	M	62	yes	yes	yes
FCRS2	F	70	yes	no	no/ failed screening
FCRS3	F	65	yes	yes	yes
FCRS4	F	22	no	yes	no/ dropped out during SMR training
FCRS5	F	21	no	yes	yes/ dropped out after SMR training
FCRS6	F	22	no	yes	no/ dropped out after H-reflex screening
FCRS7	F	55	no	no	no/ failed screening
FCRS8	M	22	no	yes	yes
FCRS9	M	22	no	yes	yes

Table 2.1: This table provides general information for all the participants in the study. From the left column to the right: the gender of every participant, their age, a statement of their previous training experience, the results of the H-reflex screening, and the statement whether they continued until the end of the experiments included in the thesis.

Representative H-reflexes for those participants are shown in Figure 2.8. It was possible to get a measurable H-reflex from the all the younger participants aged between 21 and 22 but not from all the older participants. The two participants that we were not able to get a measurable H-reflex, were both female one aged 55 years old and one 70 years old.

2.1.3. Discussion

Seven of nine participants had a measurable H-reflex. The two that failed on the H-reflex screening were excluded from the rest of the study. Both of the participants who we failed to measure an H-reflex from were 55+ years old. The size of the H-reflex is affected by defects in the nerves and the muscle fibers due to the process of aging [39]. Two of the participants who had a measurable H-reflex, however, they were 55+ (62 and 65) years old. Even in these participants, however, the experimenters noticed that it was necessary to test more electrode positions to find an H-reflex than for younger participants. Thus, it was possible to identify H-reflexes in older individuals using our present methods, but finding appropriate stimulation locations may require more time. A valuable direction for future work would be to identify ways to quickly iterate through many different stimulation sites to increase the speed of the screening procedure.

It was observed that postural adjustments could contribute to apparent changes in the H-reflex amplitude, which was already known from other studies [4, 49]. Change in the posture without the electrode pad movement resulted in entirely different H-reflex waves. Therefore, before stimulation,

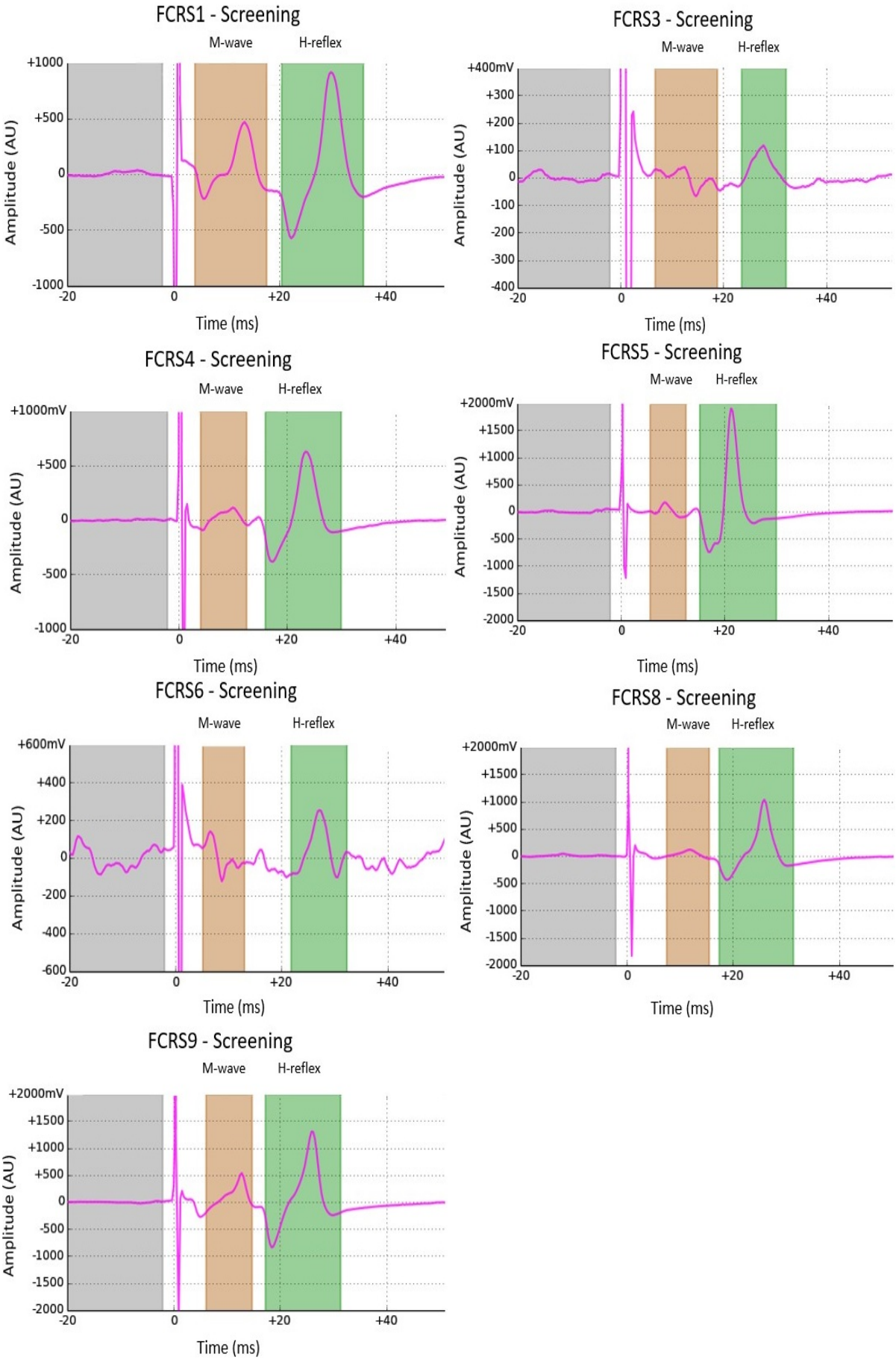


Figure 2.8: H-reflex screening results for the all participants that had a measurable H-reflex. The y-axis is in arbitrary units and the scale differs in relation to the size of the H-reflex measured. The x-axis show time in milliseconds with the gray shaded area revealing the pre-stimulus period with the stimulation happening at time zero. The orange shaded area shows the M-wave and the green shaded area the H-reflex.

the posture of the participants was corrected to be as symmetrical as possible by the coronal and transverse plane. Ideally, it was desired for the participants to be able to reproduce the posture they had during the screening for all the training sessions. Because this was not always feasible, the posture should be monitored by the operator during the sessions, and the electrode pad placement should be re-calibrated and tested in every session.

Finally, it should be noted that the representative H-reflexes are shown in Figure 2.8 in arbitrary units since during this screening we were interested in detecting an H-reflex and not optimizing it (i.e., find the placement of the electro pads on the skin that gives the largest H-reflex using the smallest amount of stimulation current). Therefore, the exact size of the H-reflex was of no interest during that procedure.

2.2. SMR Screening

The purpose of the SMR screening was to identify initial features (frequencies and locations) whose amplitude is maximally correlated with the participant's task of moving or imaging moving their hands. These initial features describe the electrode location and the frequency where the participant currently has—and likely will continue to develop—control of their brain rhythms measured with EEG. The screening was essential for all participants due to the considerable variability in the frequency and the electrode location of these features across individuals. It is important to note that the initial features provide a starting point for the training, but they can be changed as training continues [25].

Our enhanced H-reflex operant conditioning protocol was designed to help people learn to modulate the H-reflex of their right FCR muscle. Therefore, the electrodes of interest were expected to be over the right-arm area of brain homunculus (e.g., electrodes C1, C3, and CP3). Thus, we concentrated our analysis on these electrodes.

2.2.1. Method

Hardware

Sixty-four channels of EEG data were recorded from each participant using EEG caps (Electro-cap International Inc., OH, USA) with the International 10-20 method electrode placement. All EEG electrodes were referenced to the left mastoid. EEG signals were acquired with four gUSB amplifiers of 16 channels each (g.tec GmgH, Schiedlberg, Austria). The channels were digitized at 256Hz. During signal acquisition, the preamplifier filters were set to notch filter 60Hz frequency and bandpass filter frequencies between 0.5 and 62 Hz. Real-time data processing was performed on Dell computer (Dell Technologies Inc., Round Rock, TX), and feedback was provided to the participants using an monitor (LG Electronics Inc, South Korea).

Software

BCI2000, a general-purpose system for performing BCI experiments [40], was used for the collection of brain data and the implementation of the screening tasks described below. The experimental setup diagram used for the SMR screening is illustrated in Figure 2.9. The raw EEG signals gathered were amplified (Amplifiers) and were send to the computer (BCI2000) responsible for generating what the participants could see on the monitor as well as storing the brain data.

Experimental Procedure

The SMR screening procedure started with an explanation of the experimental task. Participants were encouraged to ask questions about the screening procedure. Then, an EEG cap of an appropriate size was chosen. The choice of cap size was based on the circumference of participants head. The measurements used for positioning of the cap were the total length from the Nasion (bridge of the nose) to the Inion (occipital pretu-berance) according to the International 10-20 cap system and the entire circumference of the head. When correct placement of the cap was assured, the gelling of all the electrodes followed with ECI Electro-gel (Electro-cap International Inc., OH, USA). This procedure was performed with participants seated in a supplementary chair in the lab used specifically for that purpose. When the gelling of all the electrodes was finished, participants changed to a comfortable reclining chair used for SMR experiments (Figure 2.10).

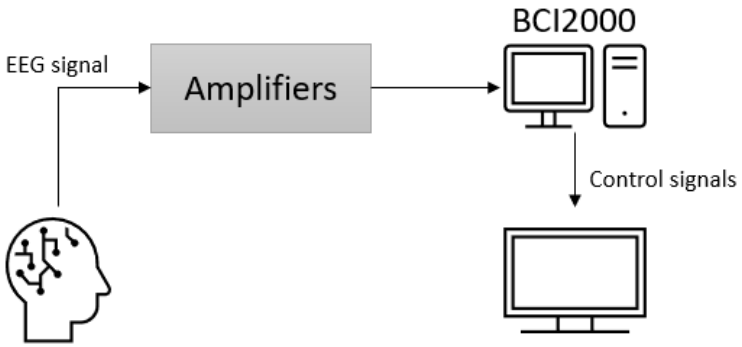


Figure 2.9: The setup that was used during the SMR screening in a diagram. EEG signals are acquired and amplified before they get processed from a computer using BCI2000. BCI2000 processes the EEG data and outputs the appropriate control signals that are displayed on a monitor. These visualizations on the monitor provide feedback to the participants.

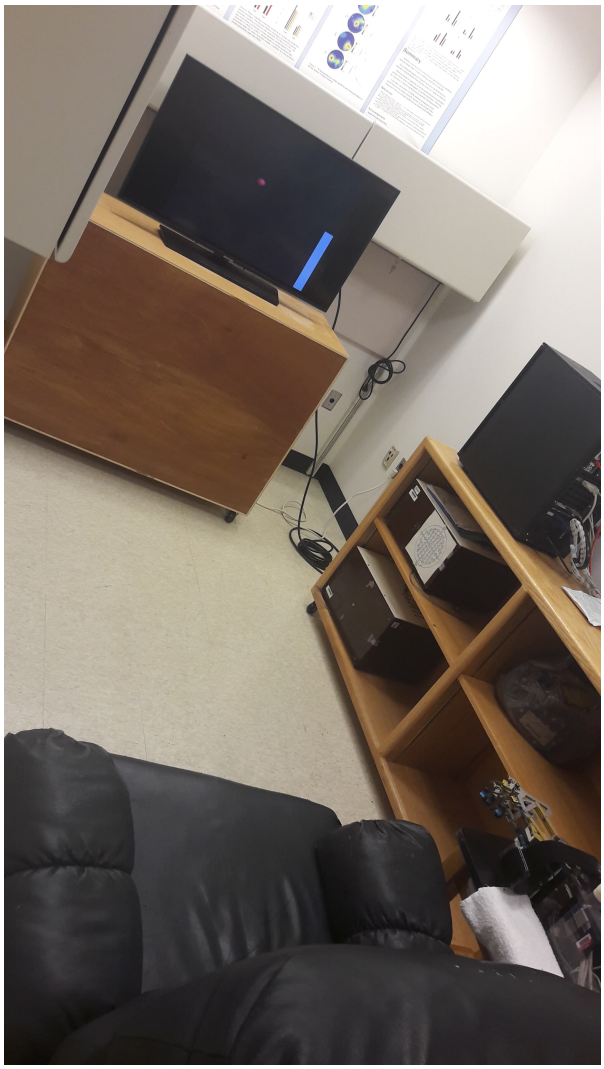


Figure 2.10: The chair and the screen used for the SMR training. The chair was located three meters away from the screen. This set up was used for the SMR screening and the SMR training that is described in Chapter 3. Participants are requested to relax their arms on the chair and minimize their movements.

After the initial gelling of the electrodes, visual inspection of the raw EEG signals (using BCI2000)

was used to identify channels with noise or artifacts. The lights in the room were then dimmed and the participant was asked to rest their arms on their legs and minimize their movements during the screening task.

Experimental Tasks

The SMR screening consisted of two tasks: (1) movement and (2) imagined movement of the right and left hands. Participants performed four runs of each task with a one-minute break between runs. Each run contained 21 trials. During each trial a target was randomly presented on the left or the right edge of the screen. For each trial, participants were instructed to move the left or right hand to the presented targets. Only after participants were ready, each run started. A “Be prepared” text sign appeared on the screen for two seconds. During that time, participants were expected to be relaxed and get ready for the task. When the two seconds pass, a target appeared randomly at on the edge of the screen (either on the right or left edge, Figure 2.11). Participants were expected to move their left or right hand, respectively, according to the position of the target on the screen. After approximately four seconds, the screen turned black, and participants were expected to relax.

This procedure continued until 21 trials had been completed consisting of one full run. The next run was imagined movement that principles were kept the same as in the description above. Instead of actual movement, participants had to imagine moving their hands when a target was visible. When the eight runs were completed, participants were provided with towels, shampoo, and hair drier to remove the excess gel that remains on their hair after the removal of the EEG cap.

Figure 2.11: Visual cues used during the screening task. The left target indicated the movement or the imagination of movement of the left hand and the right target of the right hand respectively. The targets appeared randomly on the right or the left part of the screen one at a time.

Data Analysis

The BCI2000 Offline Analysis tool was used for the data analysis of the SMR screening data [40]. The tool was modified to implement a large Laplacian filter for spatial filtering of the data [24]. The large Laplacian is a high-pass spatial filter that is particularly effective when focusing on a specific area of the scalp as in our analysis [44]. The Laplacian method includes the second derivative of the instantaneous spatial voltage distribution for each channel location. The Laplacian value of an electrode location was then calculated by combining the value of the location with the values at the four next-nearest neighboring electrodes [24]. For example, the value for channel C3 was given by the following formula, where C3’ is the Laplacian value of that location:

$$C3' = C3 - (Cz + P3 + T7 + F3)/4 \tag{2.1}$$

Feature and spectra plots, as well as topographies, were generated. The feature plots display the R^2 values between the average signal for imagery and the average signal for rest as a function of frequency for the electrodes of interest—C1, C3, and Cp3. “The coefficient of determination, or R^2 value, is a statistical measure computed over a pair of sample distributions, giving a measure of how strongly the means of the two distributions differ in relation to variance. In a BCI context, the coefficient of determination is computed for signals that have been measured during two different task conditions, and represents the fraction of the total signal variance that is accounted for (“determined by”) by the task condition. It is a measure of how well the original task condition (“user intent”) may be inferred from

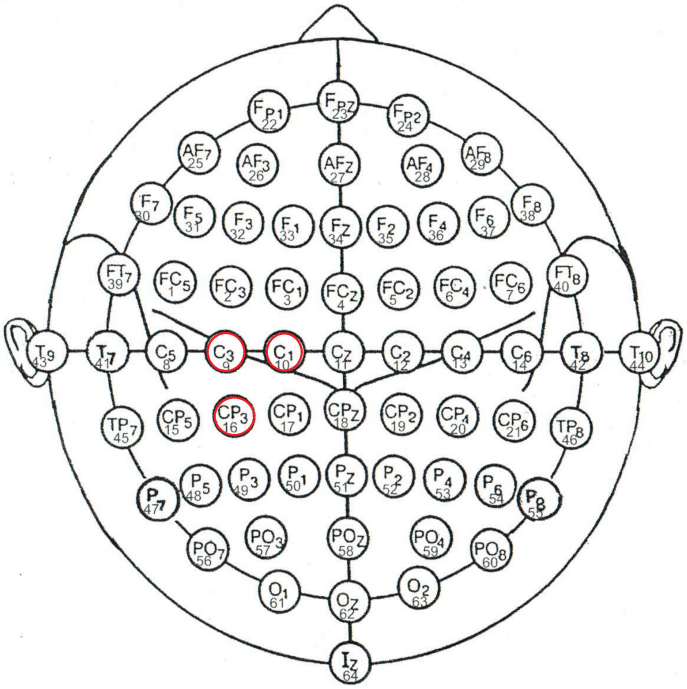


Figure 2.12: The 64-electrode montage used for the generation of topographies (nose facing up). The electrodes of interest are electrodes C1 (electrode number 10), C3 (electrode number 9) and Cp3 (electrode number 16).

Participant	Electrode	Frequency
FCRS1	Cp3	10Hz
FCRS3	Cp3	18Hz
FCRS4	C3	12Hz
FCRS5	C3	12Hz
FCRS8	C3	12Hz
FCRS9	Cp3	10Hz

Table 2.2: The initial features selected for every participant of the study with selected frequencies belonging to mu and beta frequency bands and selected electrodes being one of he C3 and Cp3.

a brain signal.", [1]. R^2 plays a significant role in the selection of the initial feature because it reflects the total variance in an EEG feature that is accounted for by the target position [43] with its range being from 0 to 1. The spectra plots show amplitude as a function of frequency and reveal how data behave at the selected electrodes. Finally, topographies, illustrating the R^2 values for the electrodes' location, were generated to show how data behave at the selected frequency. The montage used for the generation of the topographies is shown in Figure 2.12.

The initial features for the SMR training were selected using the results of the data analysis of the screening data. The initial features were typically the electrode and frequency (in mu and beta bands) that to had a higher R^2 value.

2.2.2. Results

From the seven participants with a measurable H-reflex, six proceeded to SMR training since one dropped out after the H-reflex screening (Table 2.1).

The initial features that were selected for each participant can be found at the Table 2.2. The selected frequencies ranged from 10 Hz to 18 Hz with five out of six belonging to the mu frequency band. Furthermore, all of the participants showed higher R^2 value in one of the electrodes C3 and Cp3 and none of them at C1. The R^2 value ranged from 0.0411 to 0.2193.

For the selection of the features, the highest R^2 corresponding to a specific electrode and frequency

in mu and beta frequencies, was taken into consideration. Ideally, we expect to see a peek at a small and focused frequency band. The frequencies above 26 Hz did not play a role in the final selection of the initial features because they are produced mostly from muscle activation, and they do not reflect SMR activity. We confirmed using spectra and topographies that the frequencies and the channels selected, were in the mu or beta range and the spatial response was focused over the area of the motor cortex typically responsible for hand movement.

For participants FCRS1 and FCRS9 the R^2 was highest at the electrode Cp3 around 10 Hz, for FCRS3 at C3 around 10 Hz, and for FCRS4, FCRS5, and FCRS8 at C3 around 12 Hz (Figure 2.13). Especially for participant FCRS3, previous knowledge was used for the selection of the frequency. FCRS3 was previously trained in the part in the range of beta frequencies around 18Hz. Therefore, we chose that frequency for this experiment as well. FCRS1 also had previous experience, the current screening was in accordance with their previous one; thus, no intuitive decisions were made. Dennis McFarland contributed to the selection of all the initial features for all the participants.

In Figure 2.13, the feature plots—R^2—of all the screened participants are presented. The grey shaded area shows the highest R^2 for every participant, which was the one selected as the frequency for the SMR training. The shaded area expands +/- 1 Hz from that selected frequency. Especially for participant FCRS3, there is a supplementary shaded area in the purple color that shows that the highest R^2 that would have been chosen if previous knowledge had not been taken into account. The solid green line corresponds to electrode C3, the dotted purple to electrode C1, and finally, the dashed orange to electrode Cp3.

The spectra plots indicate the difference between the participants resting EEG state and their EEG during movement or imagined movement state. Therefore, the spectra are only presented for the electrodes that were selected according to the feature plots. The spectra of the chosen electrode during imagery on the left and during movement on the right for every participant are shown in Figure 2.14. The gray shaded area shows the frequency that was selected, and the purple for FCRS3 shows the frequency band where the highest R^2 appeared.

Furthermore, the topographies were produced that correspond to each participant's chosen frequency used for the SMR training with the three electrodes of interest marked (Figure 2.15).

2.2.3. Discussion

The initial feature (electrode and frequency) selected for training is an educated guess. In other words, these features can be changed throughout the SMR training multiple times. The explanation is that the screening task is different than the actual task during the training; participants perform the actual movement, which is not the case during the training sessions. Despite that difference, the screening can reveal valuable information on what areas of the brain are used during actual movement and if those are the same during imaginary movement. It is an indication of how intense is the activation during imaginary movement versus during the actual movement. The operator can use those results for further analysis or to identify whether actual movement occurred during the training sessions.

An additional explanation is that the initial features selected can change due to the adaptation of the participant to the system and the adaptation of the system to the participants' behavior [42] (Figure 2.16). Participants and the system are considered to be two dynamic processes. As the training progresses, they adapt to each other—the user through the provided feedback of the cursor and the system through parameter adaptation (i.e., auto-regressive model and regression functions).

Furthermore, the features are selected that had been proven to be efficient in the past for a particular individual may not be ideal for that person at a later time. Changes in the nervous system (i.e., neuroplasticity) happen as the person ages are the most significant reasons for that mismatch, but further studies need to be conducted. The selection of features for the participant FCRS3 was such an example. This person was trained to modulate their SMR under a similar protocol as the one we use in this thesis and they showed higher control on the beta frequency band than the alpha band. As will be presented during the SMR training results in Chapter 3, the selection of the features according to the previous SMR training that FCRS3 participated in did not lead to the amount of control that person had previously acquired.

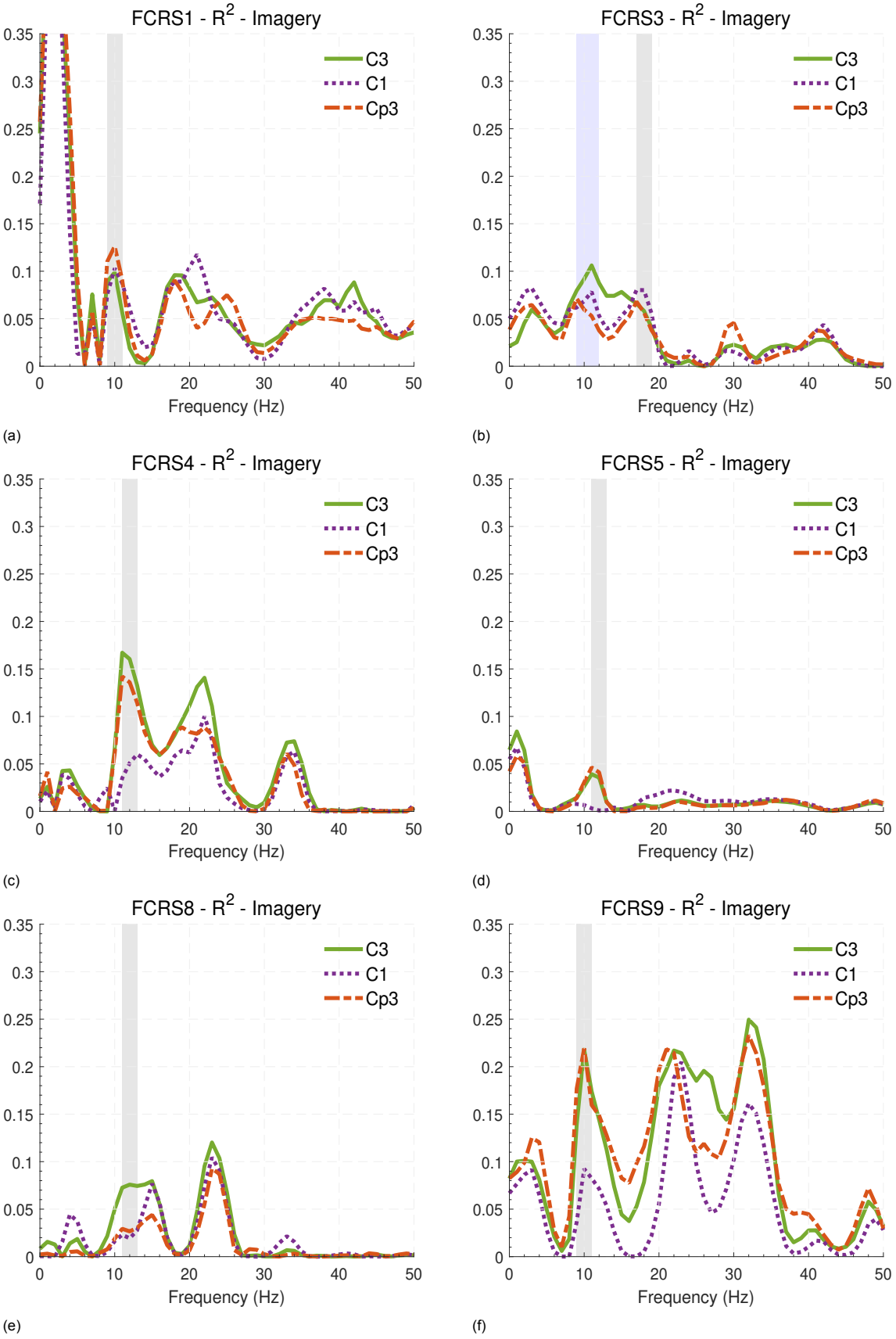
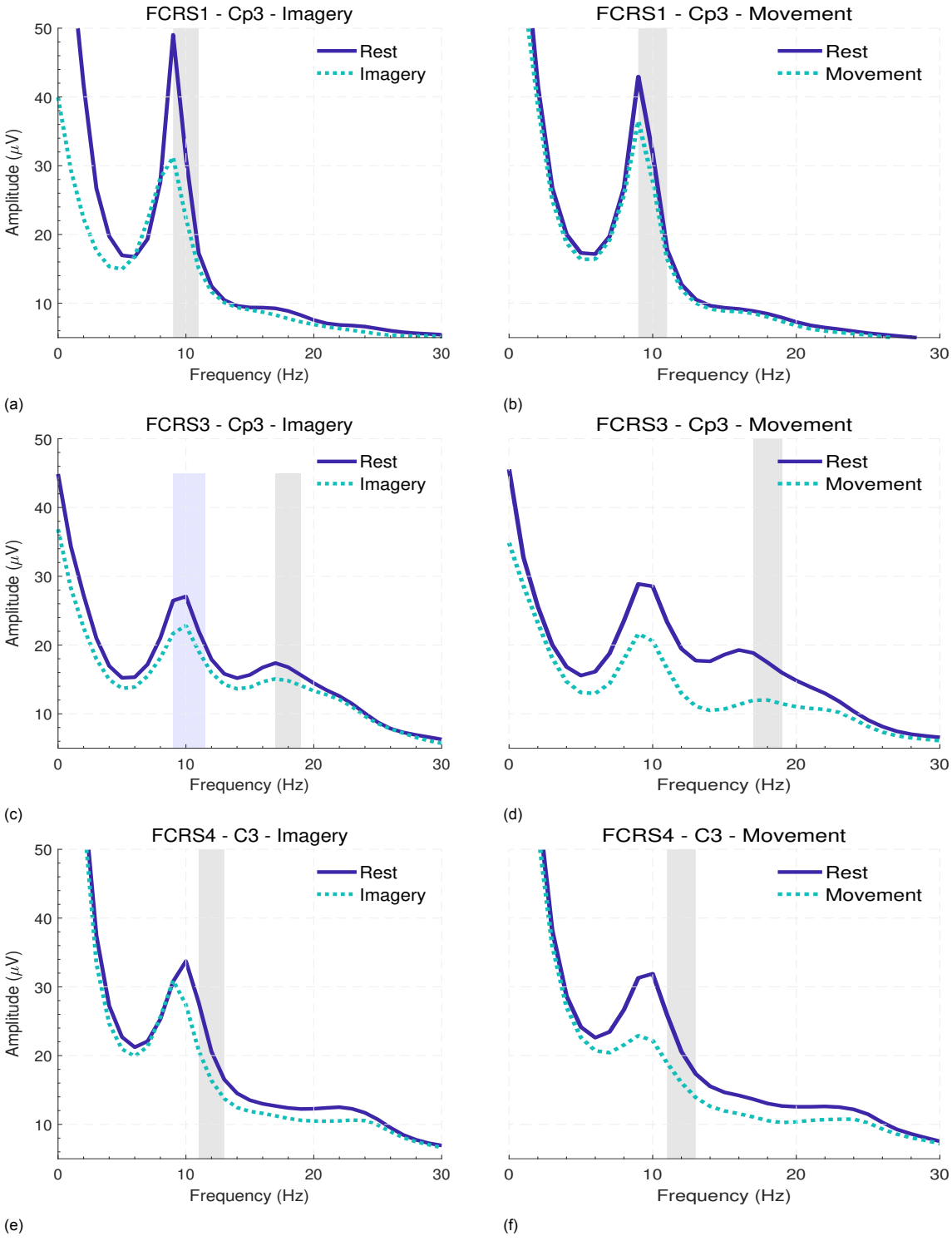


Figure 2.13: Feature plots—the R^2 values between the average signal for imagery and the average signal for rest, as a function of frequency for the electrodes C1, C3 and Cp3—from the SMR screening. The areas of interest are mu(8-12) Hz and beta (18-26) Hz frequency bands. The solid green line represents electrode C3, the dotted purple electrode C1, and the dashed orange electrode Cp3. The gray shaded area displays the frequency (±1 Hz) selected as well as, within that area, whichever electrode appeared to have the highest R^2 values, was selected for the SMR training. (a) R^2 values for participant FCRS1 (b) R^2 values for participant FCRS3. The purple shaded area shows highest R^2 values identified that was nevertheless not selected as an initial feature due to previous knowledge about this participant's abilities to modulate their SMR at the beta frequencies (c) R^2 values for participant FCRS4 (d) R^2 values for participant FCRS5 (e) R^2 values for participant FCRS8 (f) R^2 values for participant FCRS9.


FCRS1 - Cp3 - Imagery
Rest
Imagery
Amplitude (μV)
Frequency (Hz)
(a)
FCRS1 - Cp3 - Movement
Rest
Movement
Frequency (Hz)
(b)
FCRS3 - Cp3 - Imagery
Rest
Imagery
Amplitude (μV)
Frequency (Hz)
(c)
FCRS3 - Cp3 - Movement
Rest
Movement
Frequency (Hz)
(d)
FCRS4 - C3 - Imagery
Rest
Imagery
Amplitude (μV)
Frequency (Hz)
(e)
FCRS4 - C3 - Movement
Rest
Movement
Frequency (Hz)
(f)

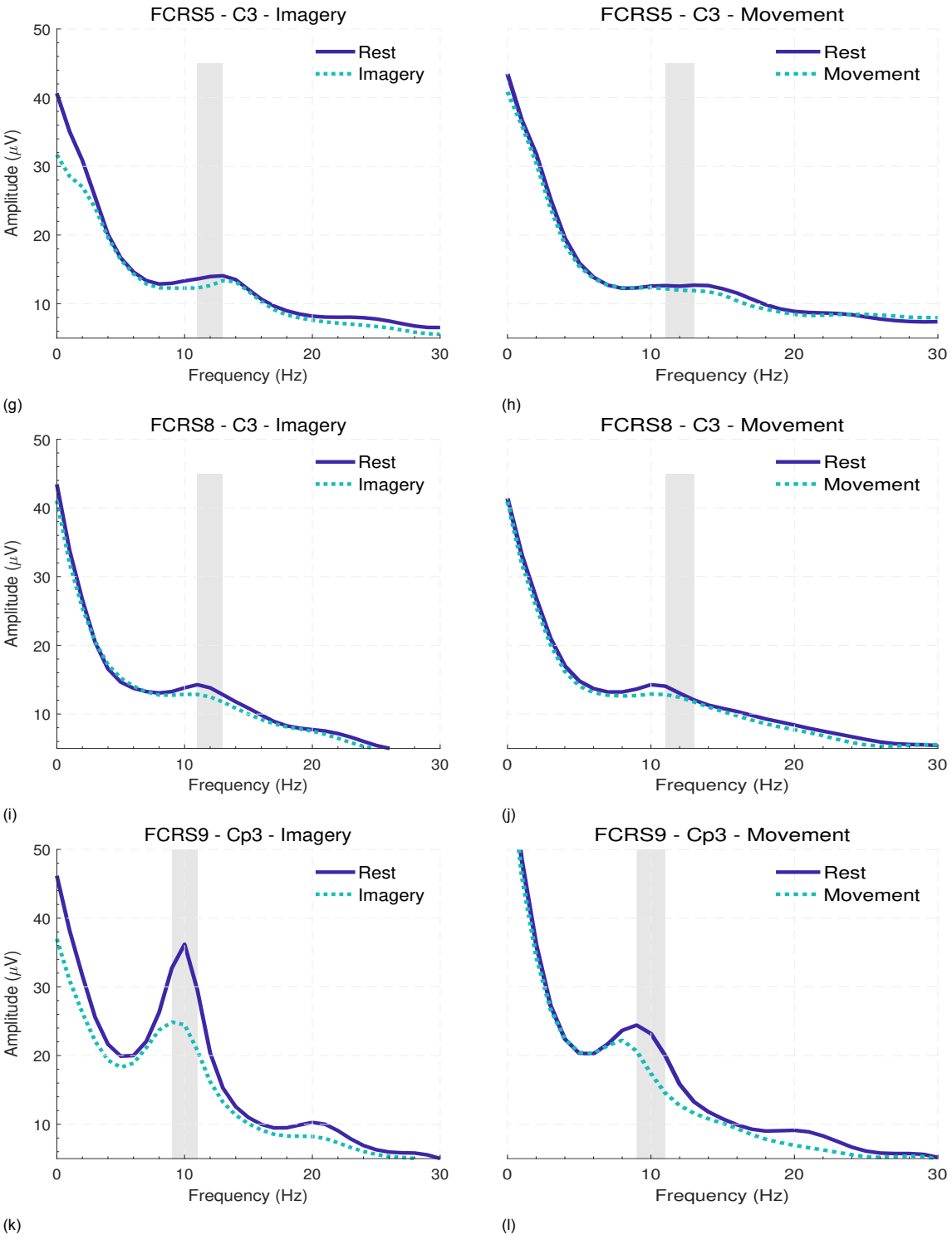


Figure 2.14: Imagery versus rest (left) and movement versus rest (right) average spectra of the EEG for each participant's selected electrode with the gray shaded area representing the selected frequency (±1 Hz) during SMR screening. The solid blue line shows the recorded amplitude (μV) during rest, and the turquoise dotted line shows the recorded amplitude during imagery or movement. (a)(b) Average spectra for participant FCRS1 (c)(d) average spectra for participant FCRS3 with the purple shaded area depicting the frequency that higher R^2 value was identified,(e)(f) average spectra for participant FCRS4 (g)(h) average spectra for participant FCRS5 (i)(j) for participant FCRS8 (k)(l) average spectra for participant FCRS9.

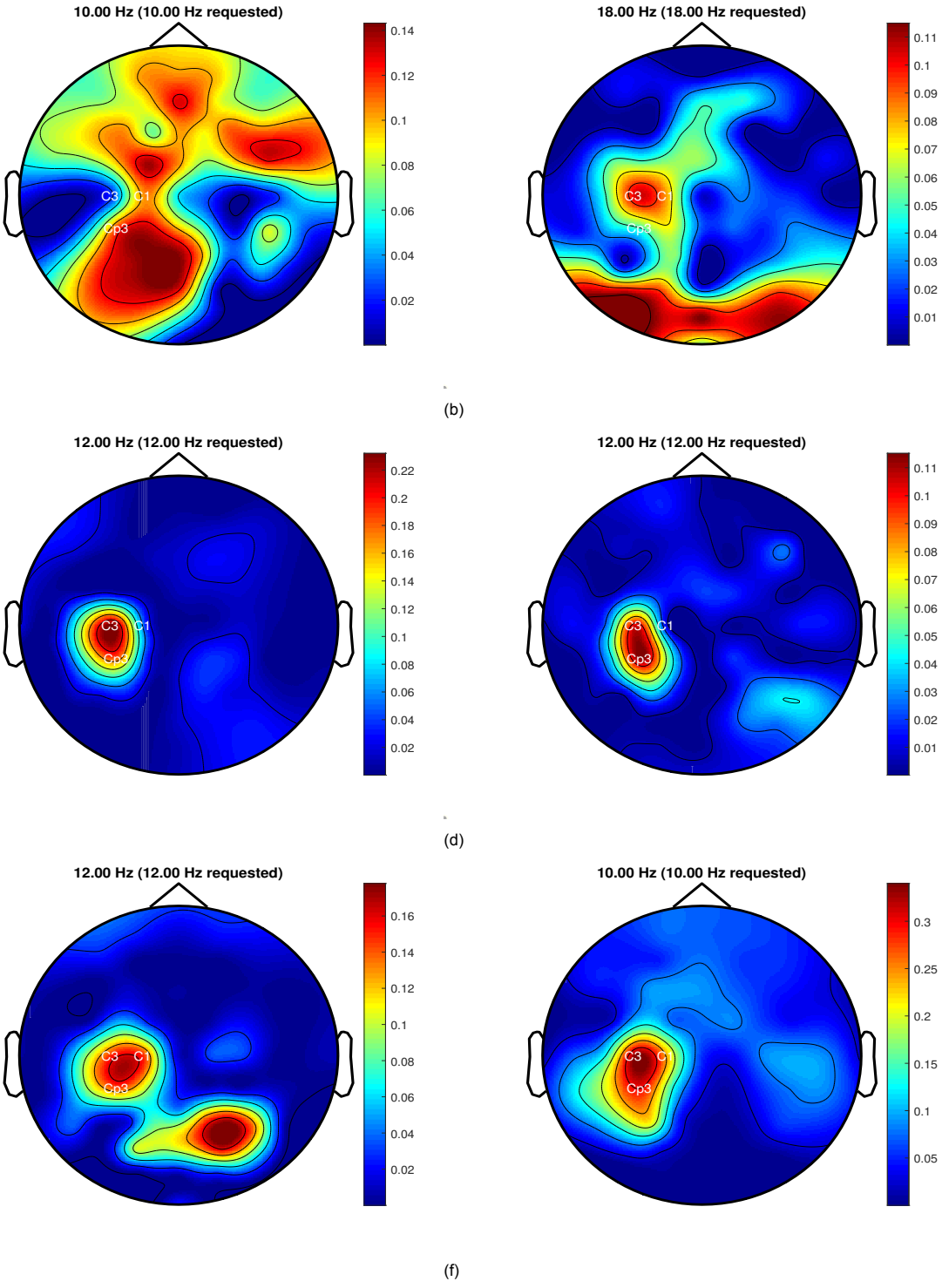


Figure 2.15: Scalp topographies between the imagery and rest state for each participant's selected frequency during screening with C3, C1, Cp3 marked. (a) topography of participant FCRS1 (b) topography of participant FCRS3 (c) topography of participant FCRS4 (d) topography of participant FCRS5 (e) topography of participant FCRS8 (f) topography of participant FCRS9.

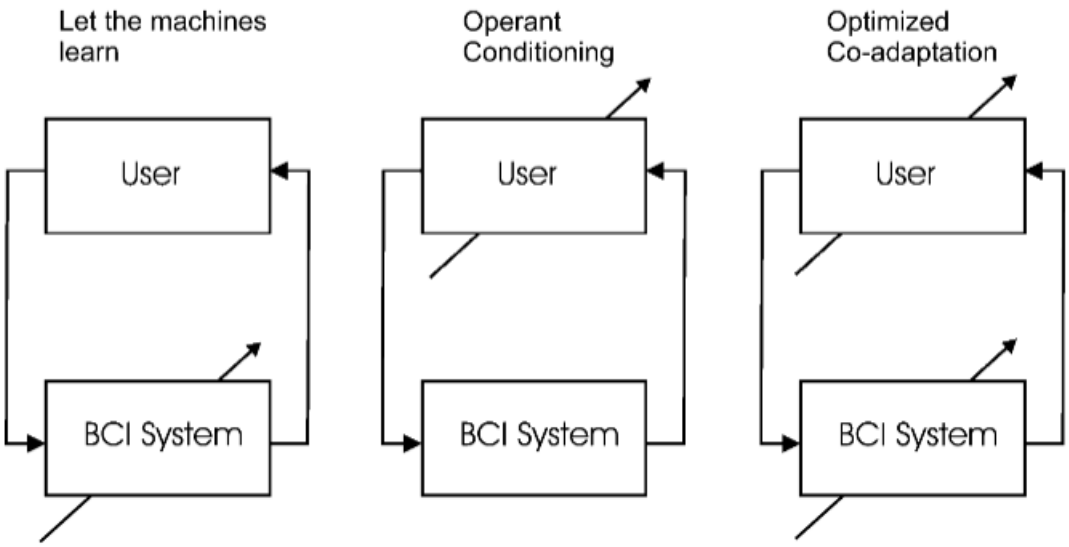


Figure 2.16: Three approaches to adaptation in the BCI design. The arrows indicate adaptation. From left to right, BCI system only adapts to the user, only the user adapts to the BCI system, and both the user and the BCI system adapt to each other. (From McFarland et al.)

3

Sensorimotor Rhythm Training

SMR training is a protocol for teaching people how to modulate brain activity in their SMC. When the training is successful, i.e., the person learns to control (increase or decrease) the amplitude of their SMRs, there is evidence that plasticity is induced in the SMC [6, 7, 9, 10]. Thomson et al. [48] showed that there is a correlation between voluntary SMR modulation and H-reflex amplitude. The magnitude of the H-reflex change observed in that study was similar to the magnitude of the task-dependent adaptation phase of the H-reflex operant conditioning (Chapter 2). As mentioned before, the task-dependent adaptation is thought to primarily reflect plasticity in the SMC.

Therefore, our participants needed to be able to voluntarily modulate their SMR for the assessment of its effects on the enhanced H-reflex operant conditioning protocol. Here, we follow the SMR training protocol of Wolpaw et al. [59], in which the SMR recorded from SMC was trained during one-dimensional cursor control [53].

3.1. Method

3.1.1. Participants

Seven participants had a measurable H-reflex (Chapter 2); two, however, decided not to continue with the experiments. Five participants (three male and two female, ages 21-70) completed the SMR training.

3.1.2. Experimental Setup

Figure 3.1 shows the closed-loop real-time BCI system used during the SMR training protocol including the acquisition of the brain signals and processing, their translation to device commands, and the visual feedback provided to the user. The recording parameters, the hardware, and the software were identical to those used during the SMR screening (Section 2.2), but the task performed by the participants was different.

3.1.3. Experimental Procedure

For each subject, SMR training consisted of a series of training sessions (at least 10) that lasted $\sim$ 40–50 minutes each, with every session including eight runs of 32 trials. Participants were familiarized with the concept behind the training and were allowed to ask questions about the task. A detailed description of the training task was given to them in the first session before the EEG cap was set up. The same setup procedure for the EEG cap was followed as during the SMR screening. After the EEG cap location was verified and gel was applied in the electrodes, participants were asked to sit in a chair $\sim$ 3 meters away from a screen (Figure 2.10).

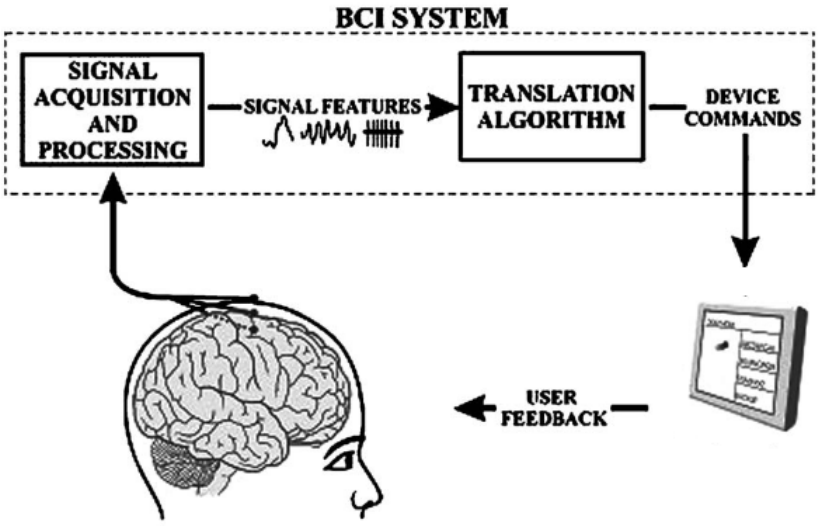


Figure 3.1: Diagram of the closed-loop BCI system used during SMR training. EEG signals were recorded from the user's scalp and passed to the BCI system. The BCI system consisted of modules. The first module, Signal Acquisition and Processing, extracts signal features that the participant was learning to control. Those signal features were transferred to the Translation Algorithm, which produced the device commands to control a device, such as the cursor used in our study. Based on the actions of the device, the user received visual feedback, closing the loop. (Modified from McFarland et al. [26])

3.1.4. Experimental Task

Participants were trained to control a cursor in one dimension using the cursor task described by Wolpaw et al. [59] and Thompson et al. [48] (Figure 3.2). When the run started, a "Be Prepared" cue appeared on the screen for two seconds. Within each trial, there was one target (a rectangle) that randomly appeared on the top or bottom-right edge of the screen. One second after the appearance of the target, feedback was provided in the form of a cursor (ball) that moved from the left to the right edges of the screen. The participants' task was to influence the cursor's vertical movement to move the cursor to the appropriate direction to hit the target by the time it reached the right edge of the screen. Participants were only allowed to influence the vertical velocity of the cursor since the cursor moved horizontally at a consistent rate from the left to the right edge of the screen; each trial lasted four seconds.

Figure 3.2: Stages of the cursor and target as they appear during the SMR training. (1) The cursor and the target appear on the screen. (2) The cursor moves across the screen at a steady rate. Its vertical displacement is controlled by the participant. (3) If the cursor hits the target, both change color and remain on the screen according to the operator's settings. If the cursor misses the target, there is no color change. (4) The screen is blank for a specified from the operator amount of time, and (5) the new trial begins. (From Thompson et al. [48])

In this task, when the participant's SMR amplitude (recorded from the appropriate EEG electrodes) increased, the cursor moved up towards the top target, and when the opposite happened, it moved towards the bottom target (Figure 3.3). If the cursor "hit" the target, then the target changed color indicating positive feedback as this was the desired performance. If the cursor missed the target, then the target and the cursor retained their colors. If there was any interruption (e.g., a loud noise) that could have interfered with the participants' concentration during the task, the run was canceled, and another run was performed instead. Participants were initially instructed to enter a state of relaxation when they saw the top target and imagine moving their right hand (or both hands) when a bottom target was on the screen. As participants familiarized themselves with the task, they could explore and change

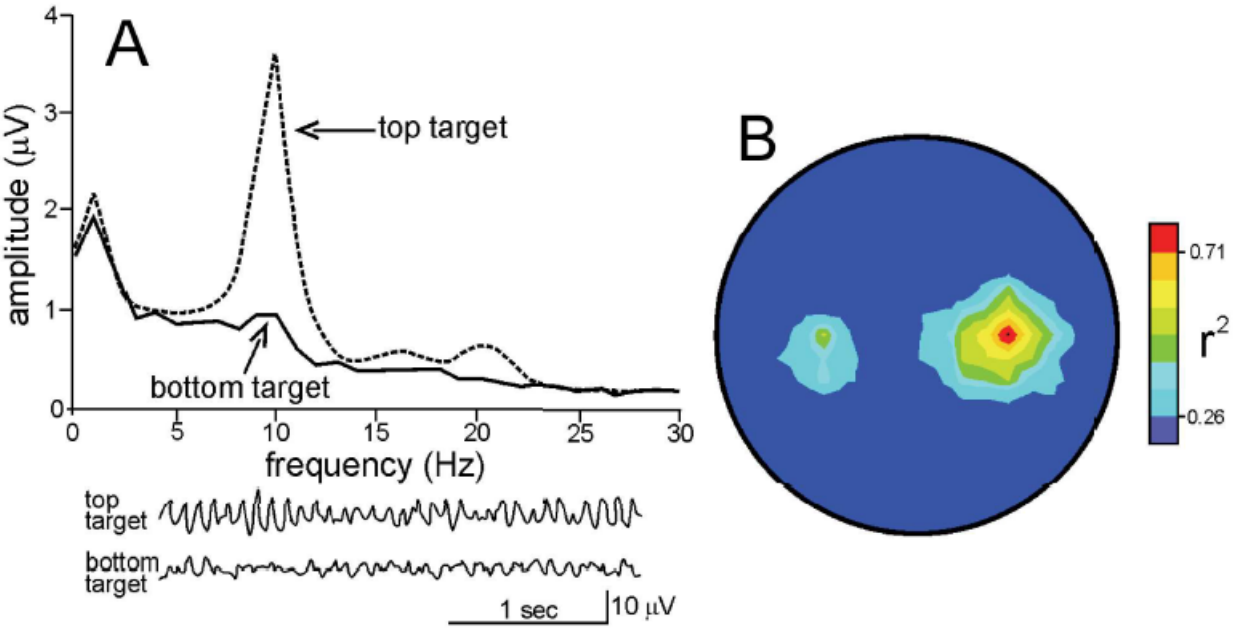


Figure 3.3: A: Average spectra of EEG over the right SMC. The dashed line describes the spectra when targets are located at the top-right edge and the solid line for targets at the bottom. The frequency that the participant has more control hitting the targets is a mu-rhythm band centered at 10 HZ. To move the cursor up, the person increases the SMR amplitude and does the opposite to move the cursor down to hit the bottom targets. Below the spectra, two EEG traces showing that SMR amplitude is high during trials with targets located up and low during trials with targets located at the bottom. B: Expected topography of the SMR amplitude showing the control to be focused over the right SMC. The orientation of the topography assumes the nose at the top. Ideally only the area above the SMC should "lights up" and the other areas of the scalp remain "silent" (indicating here by blue or small R^2 values) (From Wolpaw et al. [59])

their strategies to move the cursor to hit the targets. In general, as SMR training progressed, imagery became unnecessary because the skill to regulate SMR became more automatic, like a muscle-based action.

At the end of each run, the success rate was calculated automatically from BCI2000 described by:

$$SuccessRate = TotalHits/TotalTrials \tag{3.1}$$

with $TotalTrials$ being 32 in that specific training. At the end of the session, the operator calculated the average success rate of the participants' performance by averaging the individual success rates of the eight runs.

3.1.5. Signal Processing of the BCI System

The signal processing of the EEG data was based on previous work implemented by McFarland and Wolpaw [25, 26, 59] (see dashed rectangle of Figure 3.1).

Vertical cursor movement was based on the amplitude of EEG signals from predetermined electrodes and frequency bands. Those features were established during the SMR screening session prior to training and were inserted into BCI2000 as parameters. Successful SMR training requires adaptation to occur for both the participants and the system [42]. Participants have to learn to control the EEG feature that determined the cursor movement. Simultaneously, the system has to extract the appropriate EEG feature from background noise using signal processing techniques and translate it to appropriate control signals. Therefore, during the cursor task, instantaneous feedback should be provided to the user. This requires successful feature selection, feature extraction, and feature translation as the acquired brain signals should be processed with minimal time delay.

Feature selection was based on the offline analysis of data from prior sessions. This analysis was mostly based on R^2, which reflected the total variance in an EEG feature that was accounted for by the target position. The higher the R^2 (maximum = 1), the better the control the participant had over that feature; in contrast, if an R^2 of zero meant that the participant had no control of the selected EEG

channel. Therefore, the R^2 value indicated the participant's level of EEG control [43]. After every training session, we updated the selected channels and frequencies used for the computation of the cursor movement, only if a higher R^2 value was detected in one of the C1, C3, or Cp3 electrodes for at least two sessions.

The feature extraction method assured relatively noise-free EEG signals controlled by the participants. Feature extraction occurred in two stages. First, spatial filtering re-referenced the signal using a large Laplacian transform [24] for the improvement of signal to noise ratio [24]. This stage was followed by spectral analysis, during which mu and beta features were extracted.

The spectral analysis was an autoregressive model, a type of spectral estimator that computed a continuously-updated estimate of the spectrum of its input data. The actual weights for the model terms were estimated from blocks of EEG data (model order of 32 and window length of 400 ms). The model was updated every 100 ms.

Finally, the extracted features were translated into appropriate control signals able to assure the accurate and optimal movement of the cursor. The feature translation in the current setup included regression and normalization. The former contributed to the optimization of the predicted weights, and the latter ensured the accessibility of all the targets by the participant. It should be equally easy or difficult to move the cursor in either direction—either up or down. The cursor movement problem was modeled to minimize the squared distance between the cursor and the target. The vertical movement of the cursor was described from a linear regression function:

$$\Delta V = b(S - a) \tag{3.2}$$

where a is the estimated mean of the control signal and b is the gain term that affects the cursor step. S is the weighted sum of features, i.e., the control signal:

$$S = \sum w_i f_i \tag{3.3}$$

Equation 3.1 translates the amplitude of the selected feature into cursor trajectory 20 times/s.

Generating equally accessible targets was a simple matter of proper selection of the slope b and the intercept a in Equations 3.2 and 3.3, respectively, by:

$$a = c\mu \tag{3.4}$$

and

$$b = g\sigma \tag{3.5}$$

where μ is the mean of the signal, σ is the standard deviation of that signal, while c, and g are constants.

The intercept a was estimated by two adaptive controllers. The first controller estimated the mean over a short time, and the other removed any linear trend. The estimation of the mean was computed from a moving average of the signal, and the linear trend removal was done by an algorithm that cancels any linear trend in the percentage of targets hit. A proper estimate of the intercept was essential when the distribution of signal voltages was not symmetrical but skewed.

The last step is the normalization of the signal (i.e., a linear transformation of the signal) according to the following expression:

$$output_i = (input_i - NormalizerOffset_i) \times NormalizerGain_i \tag{3.6}$$

For each channel (denoted with the index i), an offset value is subtracted, and the final value is multiplied by the gain of the normalizer. The offset and the gain values are estimated values based on past statistics so that the output signal has zero mean and unit variance.

The spatial filtering, the spectral analysis, the regression, and the normalization comprised a cascade of operations implemented in BCI2000.

3.1.6. Data Analysis

Data analysis was performed after every training session and consisted of spectral analysis and the production of topographies with the BCI2000 offline analysis tool, as well as the conversion of mean hits per session to percentages. Based on the results, the initial features for every participant could be replaced with new ones that the participant seemed to have better control (i.e., higher R^2). The

data analysis included spectral analysis with MATLAB scripts, and the production of topographies. The average success rate was calculated for all the participants for all the sessions based on Equation 3.1 and was used as an indication of control of the SMR over the selected features. The same analysis took place after the SMR training was completed to assess the final performance of each participant.

Statistical analyses were performed with SPSS Version 25.0 software package to prove the statistical significance of the mean hit value between session two and the last session of every participant, i.e., to assess the efficacy of the SMR training on the task performance for each participant. The data were expressed as the number of contacts with targets (hits) for every run of every. The second session was selected instead of the first because it was observed that the EEG data gathered from the first session of some participants included EMG artifacts. Many participants were subconsciously moving when concentrating for the first time to the training task (e.g., some were crunching their teeth or moved their jaw). The normality of the data was tested to select between a parametric or a non-parametric test. The normality was tested with the Shapiro-Wilk test ($p<0.05$). Finally, comparisons between groups were performed with analysis of a non-parametric test–Mann–Whitney U test. A value of $p<0.05$ was considered statistically significant.

3.2. Results

Five participants completed at least 10 sessions of SMR training (FCRS4 dropped out after the sixth session for personal reasons). The average number of hits for each participant during each session (as well as the number of hits of each run within a session) are shown in Figure 3.4.

The average spectra and feature plots for each participant are shown in Figure 3.5 and Figure **??**, respectively. The feature plots for every other session for every participant can be found in the Appendix B. The gray shaded area shows the selected frequency for cursor control. Based on the offline analysis completed after each session, small deviations from the initial features were made for participants FCRS1 and FCRS5. For FCRS1, the initial feature at 10 Hz was changed for the last two sessions to 9 Hz, and for FCRS5 the initial feature was changed from 12 Hz to 13 Hz after the 9^{th} session. For FCRS3, the initial feature at 18 Hz was changed to 12 Hz during the last training. Therefore, the gray shaded area showing the frequency of the feature differs between the first and the last sessions.

Scalp topographies of SMR amplitude during the first and the last sessions are shown in Figure 3.6. Some participants had already, from the beginning a clear, focused activity over their left SMC (i.e., FCRS3, FCRS5, FCRS8).

The assessment of normality of the distribution of the data with the Shapiro-Wilk test is shown in Table 3.1. The number of hits of the last session from FCRS3 and FCRS8 were not normally distributed—highlighted with red.

Participant	Session	W	df	p-value
FCRS1	second	.915	8	.393
	last (11)	.913	8	.375
FCRS3	second	.963	8	.838
	last (10)	.807	8	.034
FCRS5	second	.977	8	.945
	last (14)	.912	8	.370
FCRS8	second	.880	8	.189
	last (10)	.808	8	.035
FCRS9	second	.989	8	.994
	last (11)	.886	8	.217

Table 3.1: Shapiro-Wilk test results. The table provides the test statistic (W) of the Shapiro-Wilk test, the degrees of freedom (df), and the p-value for every participant's second and last session. Because the last session number is different among the participants, the exact number of the last session is given in parenthesis. The red p-values highlight the cases where the null hypothesis was rejected (i.e., the data are not normally distributed according to the Shapiro-Wilk test).

Based on the Mann–Whitney U test FCRS3 ($p = 0.007$), FCRS8 ($p < 0.001$), and FCRS9 ($p < 0.001$) showed significantly higher mean values of their last session compared to the second session of the SMR training (Table 3.2). In contrast, FCRS1 ($p = 0.505$) and FCRS5 ($p = 0.798$) did not produce a

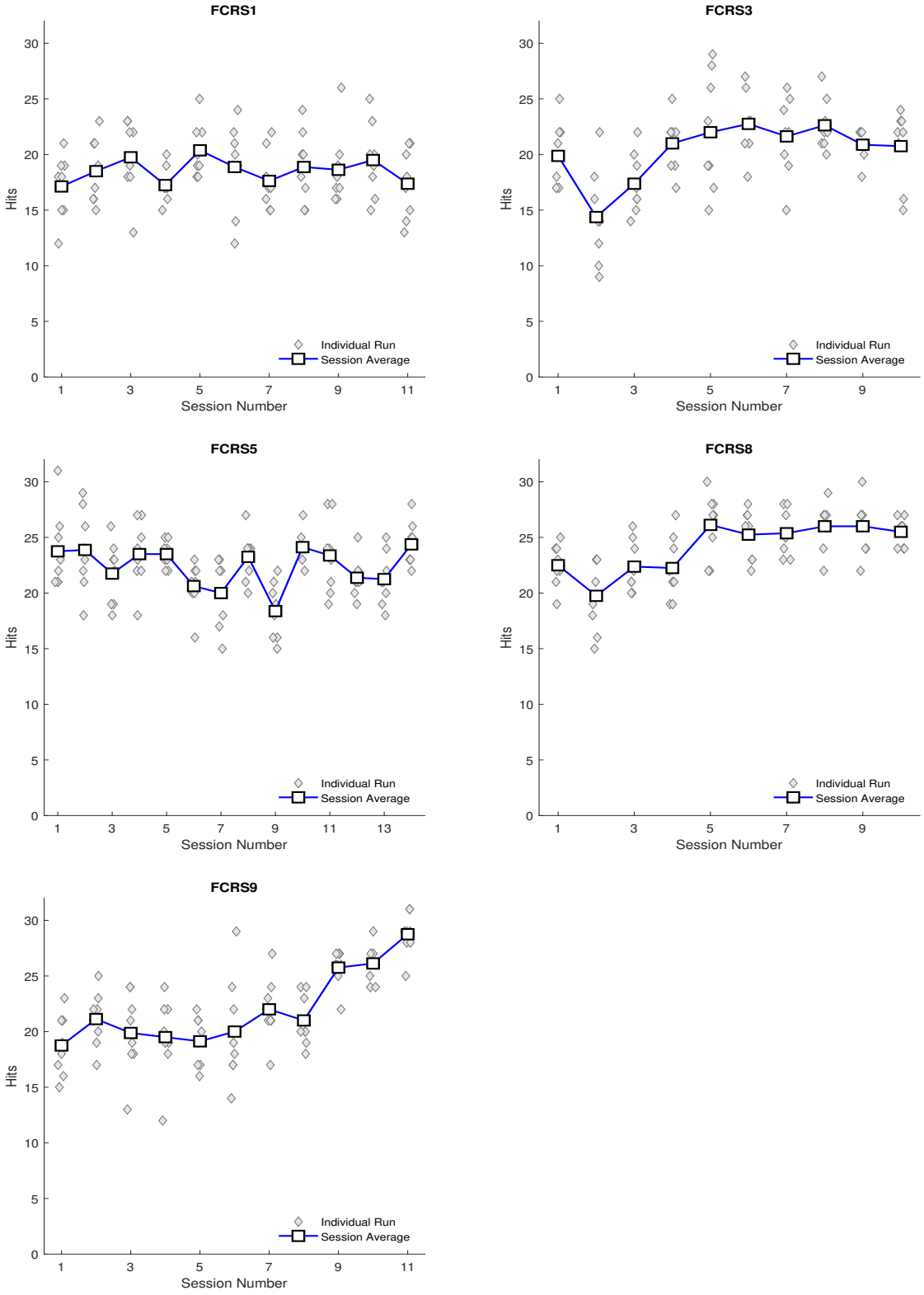
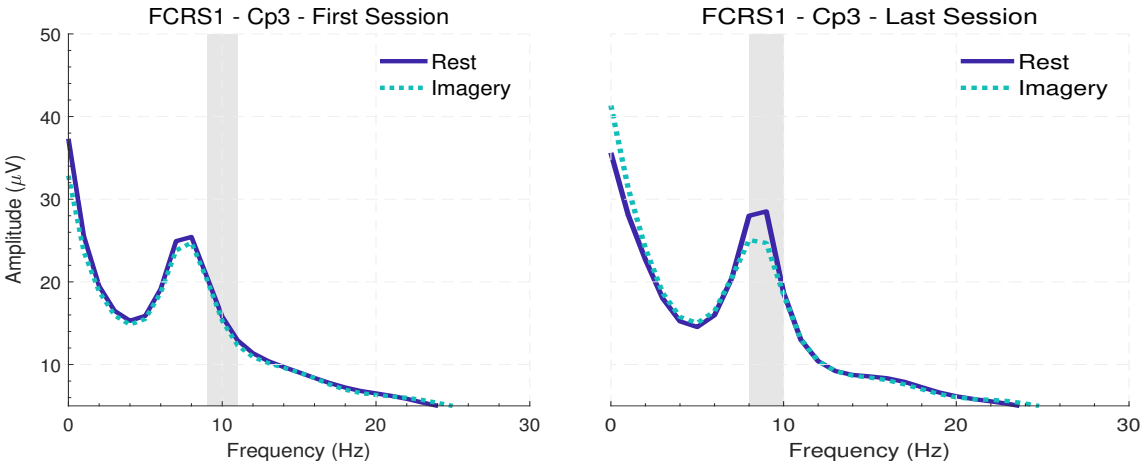


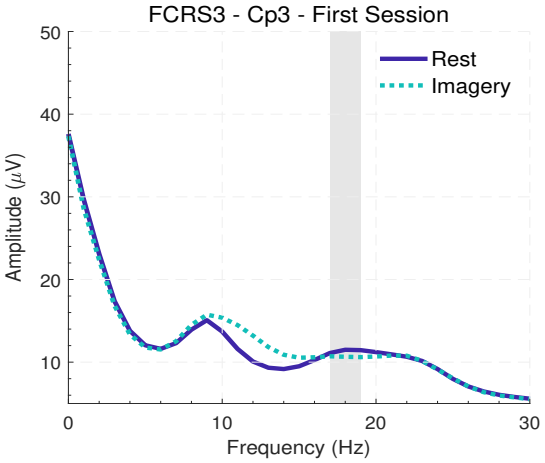
Figure 3.4: SMR Training progress for each participant. The y-axis represents the number of times the cursor hits the targets during a given session (x-axis). The white square markers represent the mean of the hits within each session while the diamond markers show the hits of an individual run.


FCRS1 - Cp3 - First Session
Rest
Imagery
Amplitude (μV)
Frequency (Hz)
50
40
30
20
10
0
10
20
30

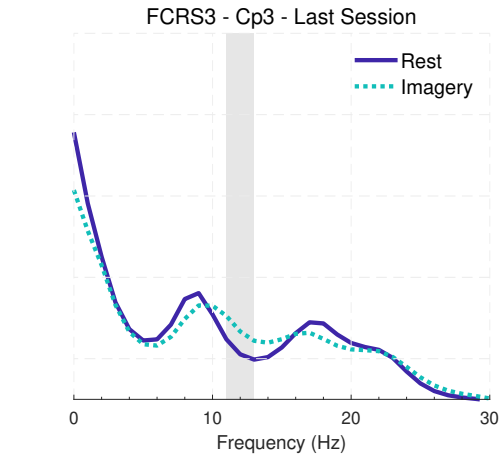
(a)

FCRS1 - Cp3 - Last Session
Rest
Imagery
Frequency (Hz)
0
10
20
30

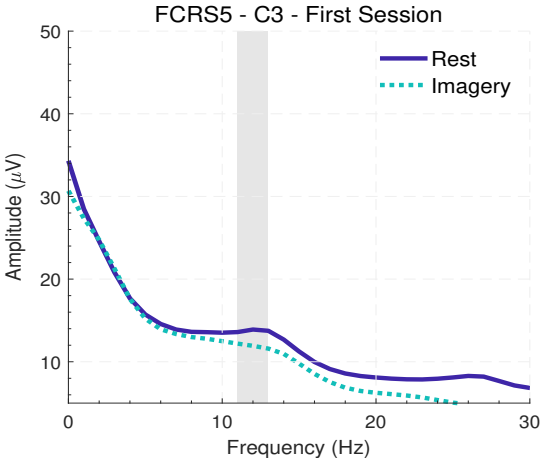
(b)


FCRS3 - Cp3 - First Session
Rest
Imagery
Amplitude (μV)
Frequency (Hz)
50
40
30
20
10
0
10
20
30

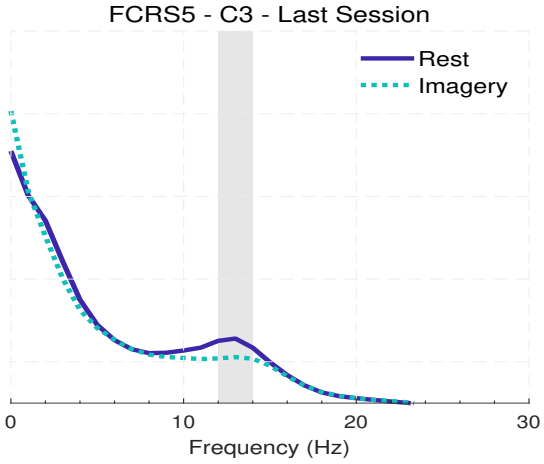
(c)


FCRS3 - Cp3 - Last Session
Rest
Imagery
Frequency (Hz)
0
10
20
30

(d)


FCRS5 - C3 - First Session
Rest
Imagery
Amplitude (μV)
Frequency (Hz)
50
40
30
20
10
0
10
20
30

(e)


FCRS5 - C3 - Last Session
Rest
Imagery
Frequency (Hz)
0
10
20
30

(f)

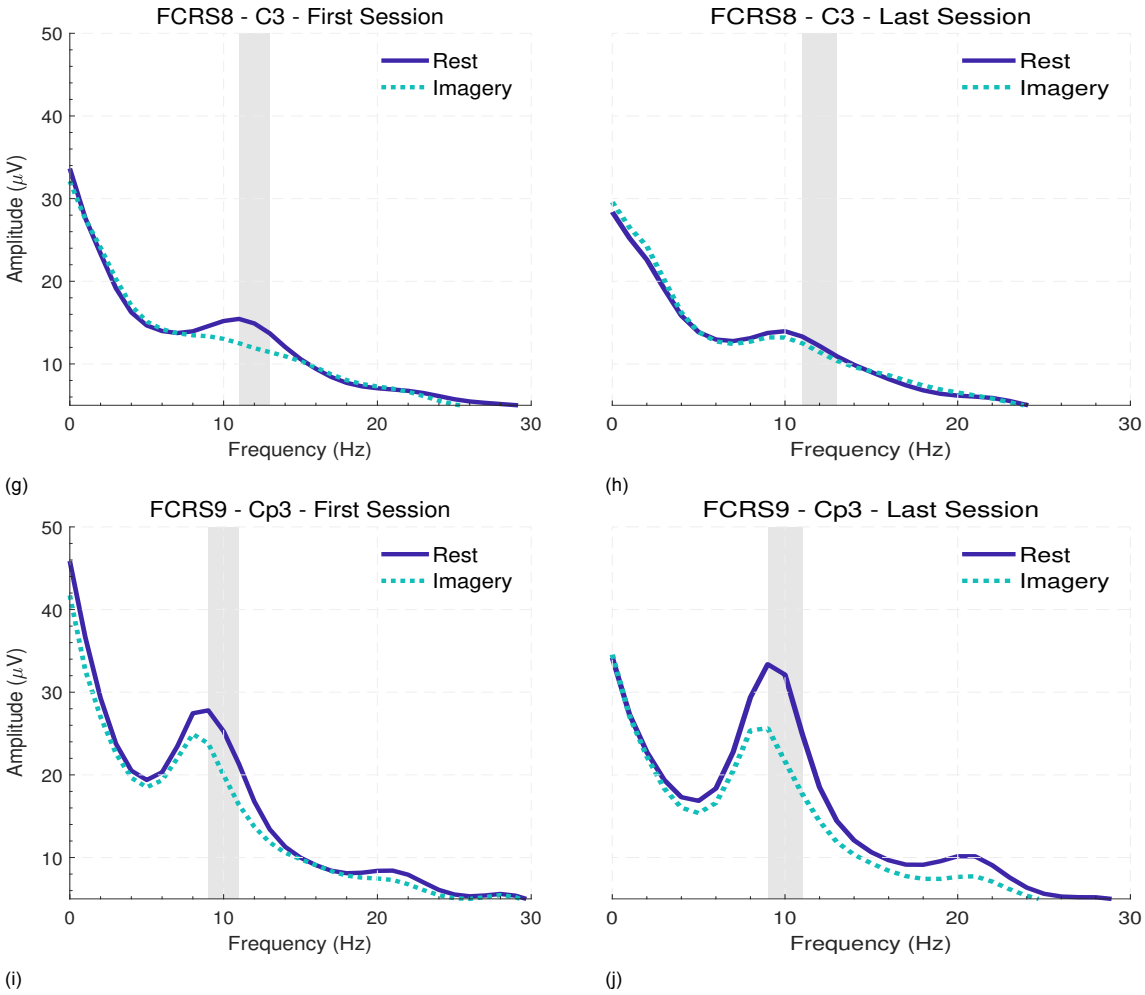
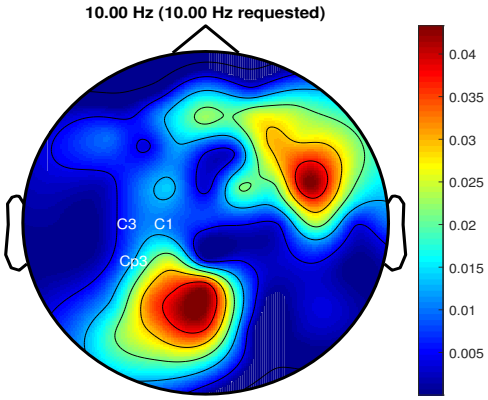
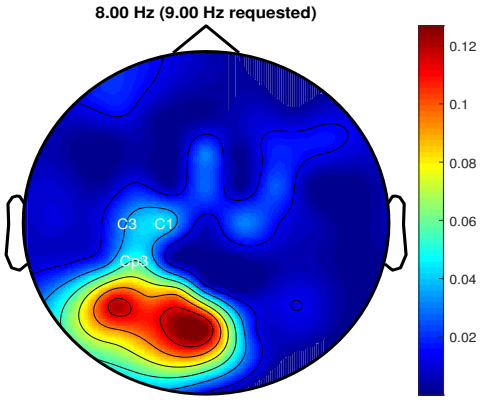


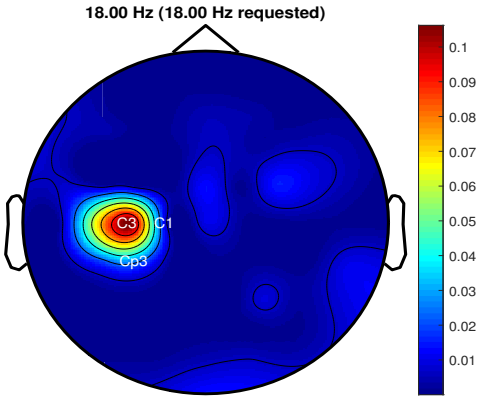
Figure 3.5: Average spectra of the EEG over each selected electrode for targets located at the top (solid blue line) or bottom (dotted turquoise line) of the computer screen from the first session (left) and the least section (right). The gray shaded area represents the selected frequency for SMR training that can be different for some participants during the first sessions compared to the last session. (a, b) Average spectra for participant FCRS1 (c, d) average spectra for participant FCRS3 (e, f) average spectra for participant FCRS5 (g, h) average spectra for participant FCRS8 (i, j) average spectra for participant FCRS9.



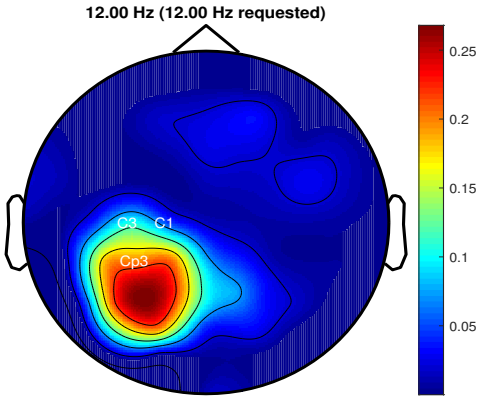
(a) FCRS1 first session



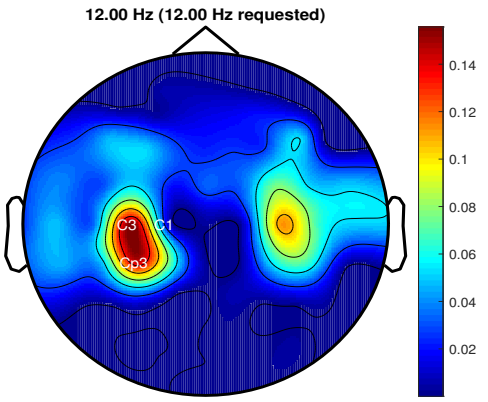
(b) FCRS1 last session



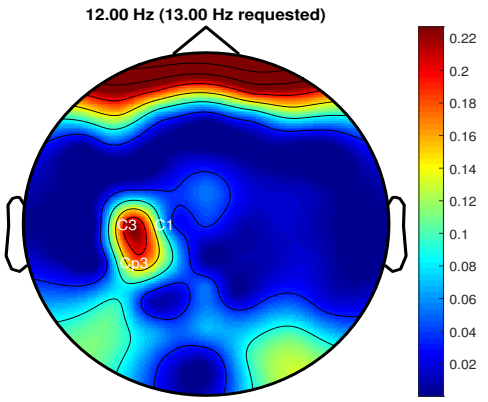
(c) FCRS3 first session



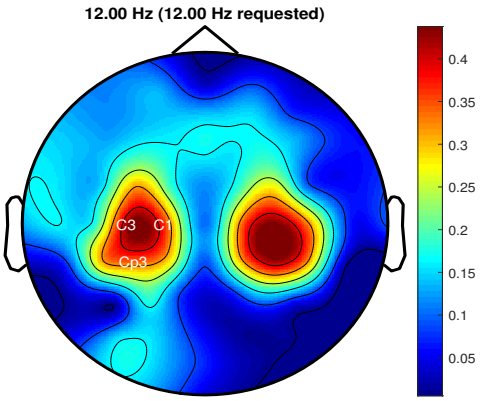
(d) FCRS3 last session



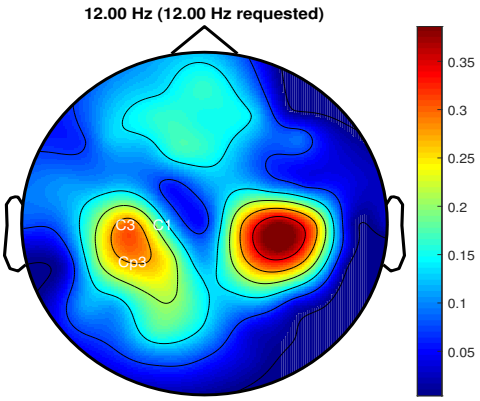
(e) FCRS5 first session



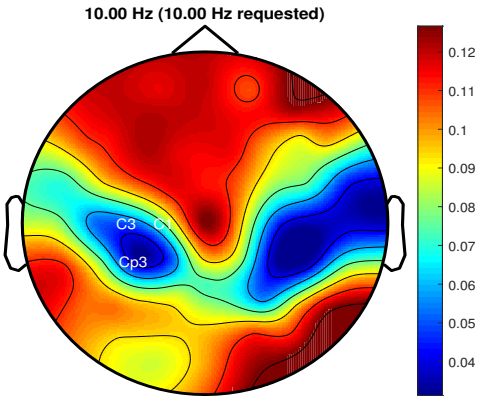
(f) FCRS5 last session



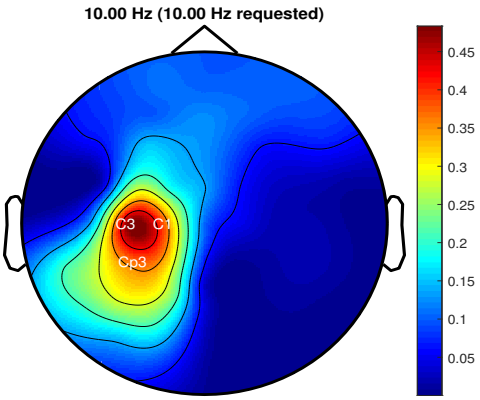
(g) FCRS8 first session



(h) FCRS8 last session



(i) FCRS9 first session



(j) FCRS9 last session

Figure 3.6: Scalp topographies of SMR amplitude control between the imagery and rest state for each participant's selected frequency during training with C3, C1, Cp3 marked. The topographies that correspond to the first training session are on the left and on the right, the ones from the last session for each participant. The selected frequency could have changed through the training and this is the reason why for some participants the first and the last topographies at a specific frequency do not match. (a, b) topography of participant FCRS1 (c, d) topography of participant FCRS3 (e, f) topography of participant FCRS5 (g, h) topography of participant FCRS8 (i, j) topography of participant FCRS9.

significant increase in task performance.

Participant	N-2	N-last	U	z-value	p-value
FCRS1	8	8	25	-.742	.505
FCRS3	8	8	7.5	-2.586	.007
FCRS5	8	8	29	-.318	.798
FCRS8	8	8	<.001	-3.393	<.001
FCRS9	8	8	.5	-3.328	<.001

Table 3.2: Mann–Whitney U test results. The test was performed for the mean values of the runs of the second and the last session for every participant. The green colored values are the statistically significant results.

3.3. Discussion

The SMR training mean value of the last session was significantly higher for three out of five participants who completed the SMR training and four out of five participants reached a mean success rate of at least 70% ($\sim$ 23 hits). The BCI is used in such a way that if there is no input to the system, the success rate will be approximately 50%, indicating that any success rate higher than that implies control produced by the participants. When the success rate is lower than 50%, it indicates that the participant produces inhibitory signals that do not allow for cursor control but that can change during the training. Therefore, the participants FCRS1 and FCRS5, who did not have a significant result based on the statistical analysis, have control of their SMR but most likely more sessions or multiple features would contribute to their improvement. All participants were trained for at least ten sessions. Typically, three to five sessions are required for people to gain control of their SMR, but depending on the participants' performance, training is often extended. Lower success rates (50%–60%) are expected during the first sessions of the SMR training since the participants had not yet acquired control over their SMRs or unexpectedly high rates (80%–90%) due to muscle activity usually of the forehead or the eyes [25]. The latter was discouraged as the ball was controlled by muscle activity instead of SMRs. A huge variability among the participants was the reason why the operator should be alerted for throughout the training to help the participant to adhere to the task requirements.

The number of sessions for each participant varied each week from two to four (depending on their availability). Participants FCR8 and FCRS9 consistently completed three sessions of SMR training per week. They also had higher success during the final sessions of their training. We cannot conclude though that three sessions per week work better than two or any other number because the population involved in the study is small, and neither a study on the most efficient number of SMR training sessions per week exists. As simple observations though from the gathered data, it can be seen that FCRS8 and FCRS9, despite having a low success rate during the beginning of the training, they show an exceptional improvement in comparison with FCRS5, FCRS3 and FCRS1 that had two sessions per week. FCRS4 had a high amount of control from the first session, but they dropped the study for personal reasons, therefore their data were not used although thy looked promising for reaching 100% success rates after 10 SMR training sessions.

We selected 18 Hz as the initial feature for FCRS3 based on the SMR training that this person had participated in the past. From the screening and during the first session was obvious that there was a prominent peak at 12 Hz. After discussion, we decided not to change it directly to 12 Hz for two reasons: First, because we expect the participant to adapt to the system [27]. Second, from the second to the fifth session, we could see continually higher R^2 at 18 Hz that could reflect the adaptation of the user to the system (Appendix B). Unfortunately, the participant experienced a bike accident after session five and had to stop the training for a week. When the participant returned to the usual training schedule, although the 18 Hz peak was still visible, it did not seem that the participant continued to have increasing control over that frequency, instead 12 Hz seemed to be the prominent one. The feature was changed during the last sessions as it was expected to help the participant to control the cursor. Nevertheless, the mean success rate during the last session (64.25%) remained stable compared to the previous session (64.625%) when the feature was different. More sessions may have been needed for the user to learn/adapt to the new cursor behavior.

Based on the visual inspection of the topographies (Figure 3.6), it is apparent that a focus activity over the left SMC is associated with the performance of the participants during their first training session. This does not guarantee that the particular participants would have better cursor control than those who

had a less pronounced activity over that area during their first session. A very characteristic example is participant FCRS9, who had a highly focused activity over their left SMC. During the first training, however, the activity in that area was low. Each participant came up with their own strategy to control the cursor. Some of them imagined movement for both of their hands, which could explain why symmetrical activity existed in these subjects over both left and right SMCs.

These results indicate that at least four participants can modulate their SMR over the SMC and that three of them showed also significant improvement throughout the training. Since during the enhanced H-reflex conditioning BCI-based feedback of SMRs is provided, we expect to see further improvement of the ability of the participants to voluntarily modulate their SMR.

4

Enhanced H-reflex Operant Conditioning Software

We propose that the present H-reflex operant conditioning protocol may be enhanced using BCI-based feedback of SMRs. The SMC drives the changes happening during the H-reflex operant conditioning (the task-dependent adaptation and the long-term change, Chapter 1) through the influence of the CST [9]. By providing participants feedback on how well they enhance that influence, we hypothesize that the progress of learning to change their H-reflex (i.e., to produce critical SMC activity leading to their H-reflex change) will be enhanced. This hypothesis is based on recent investigations [7, 9, 10, 48], showing a correlation between SMR synchronization and H-reflex amplitude, rendering SMR amplitude to be a likely EEG feature that reflects this critical SMC activity.

In this chapter, we provide an overview of the software component of EPOCS, which we use for H-reflex operant conditioning experiments and describe how we modified it for use in the enhanced H-reflex operant conditioning protocol. This new version of the EPOCS software component differs from existing versions in two ways:

1. It provides additional feedback to the participants on the amplitude of their SMR.
2. A stimulus is only triggered if the amplitude of the participant's SMR meets a criterion.

In addition, we describe how users will interact with this new version of the EPOCS software component.

4.1. Existing EPOCS Software Component

The EPOCS software component's architecture can be divided into two parts:

1. A BCI2000-based signal acquisition and processing system (written in C++) that performs all the essential functions for H-reflex operant conditioning (e.g., how long should the recorded muscle activity be within a specified range for the system to produce a stimulation pulse).
2. A python-based graphical user interface (GUI).

4.1.1. BCI2000-based Signal Acquisition and Processing System

BCI2000 is a general-purpose BCI research and development platform that can incorporate any biosignals (e.g., EEG, EMG), signal processing methods, output devices, and operating protocols. It consists of four modules that communicate with each other: the Source module, Signal Processing module, Application module, and Operator module (Figure 4.1). The Source module, Signal Processing module, and Application module are collectively known as the core modules.

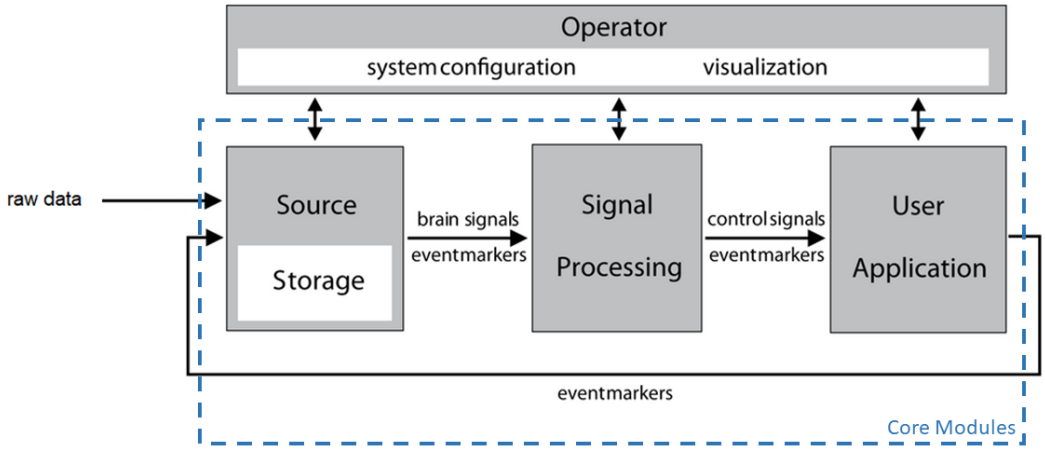


Figure 4.1: The basic modules of BCI2000. The Source module, the Signal Processing module, and the User Application module are the core modules of BCI2000. These modules communicate through a unidirectional connection. The Source module is responsible for data acquisition and storage. It passes data (in blocks) and event markers to the Signal Processing module. There, control signals are produced based on the type of signals that were collected. These control signals are passed to the User Application module, which provides feedback to the participants. The Operator module provides an interface between the core modules and the operator (system configuration and visualizations); communication type between the Operator and the core modules is bidirectional.

- Source module: responsible for acquiring data from experimental hardware and saving this data. The data are processed in blocks and then sent to the Signal Processing module. Concurrently, it receives state vector information from the application module that is saved to a file with the raw digitized data. It acts like an online system's timer that synchronizes to the A/D hardware clock.
- Signal Processing module: processes data received from the Source module and produces the control signals that are sent to the application module. The control signals are the output of internal signal processing, described in Chapter 3.1.5.
- User Application module: provides visual feedback to the participant.
- Operator module: allows viewing, editing, changing and loading system parameters and files, as well as starting and stopping system operation.

Each of the four BCI2000 modules communicate with one another using the TCP protocol. Communication between the three core modules is unidirectional (from the Source module to the Signal Processing module to the User Application and then back to the Source module). Communication between the Operator module and the three core modules is bi-directional; it is used to send and receive system commands, status updates, and parameters between the operator and the core modules.

Each of these modules can be modified depending on the needs of the specific experiment. For example, the H-reflex operant conditioning protocol uses a custom signal processing module for analyzing M-waves and H-reflexes. The SMR training protocol (Chapter 3) is also based on BCI2000. It depends on custom-written signal processing and User Application modules.

4.1.2. Python GUI

In EPOCS, BCI2000 is hidden from the user. In its place, there is a custom-written python GUI. This python GUI (Figure 4.2) communicates with the invisible instance of BCI2000. The python GUI and BCI2000 communicate with one another using shared memory. This architecture enables the following:

- It provides an operant-conditioning-specific GUI; it replaces the BCI2000 User Application module providing the participants and the researcher/therapist with the real-time feedback display on the experiments.
- It allows researchers/therapists to easily view and configure H-reflex operant conditioning protocol settings, as well as control system operation.
- It provides offline analysis tools for use with the H-reflex operant conditioning data. Based on this analysis the researcher/therapist can document the participant's performance and adjust the parameters for future experiments.

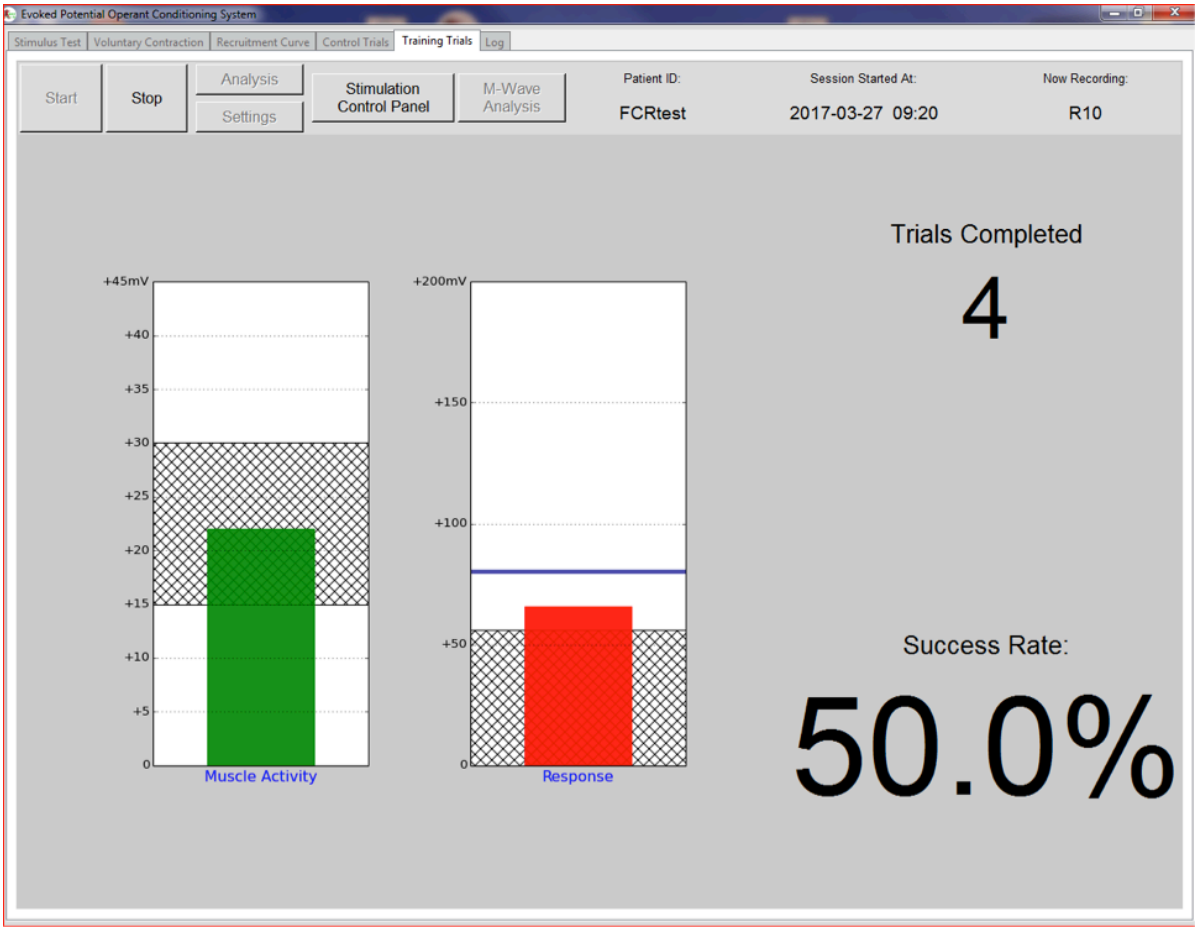


Figure 4.2: Graphical user interface of the present version of EPOCS. The bar on the left side of the figure indicates the continuously-updated amplitude of muscle activity recorded with EMG. The shaded area for the feedback bar indicates the desired level of muscle activity that the participant is expected to maintain for a specific time before the stimulation is elicited. The response bar (middle of figure) provides trial-by-trial feedback on the size of the participant's H-reflex. For the response bar, the shaded area shows the desired size of H-reflex. When the bars are within the shaded areas, their color is green else they turn red. The y-axis of all the bars is in mV. Furthermore, the trials that have been completed and the current success rate are apparent to the participant.

4.2. Enhanced H-reflex Setup

Our enhanced H-reflex conditioning system incorporates BCI-based feedback of SMRs into the present H-reflex conditioning protocol. It requires the recording of different types of two different types of physiological signals (i.e., brain signals and muscle signals), sampled with different devices and synchronized appropriately. For the realization of that setup, we combined the existing system used during SMR training (to generate BCI-based feedback) and the existing system used for H-reflex operant conditioning (EPOCS). Therefore, two different computers, each one controlling one of the acquisition devices running one of the two experimental paradigms, were used (Figure 4.3). Practically, both computers were

running BCI2000 but with different core modules for handling either EEG or EMG data synchronized over a network connection. The BCI-based feedback of SMRs, produced by the BCI-based feedback PC, is transferred to the EPOCS PC, where it is displayed from the python GUI to the participants.

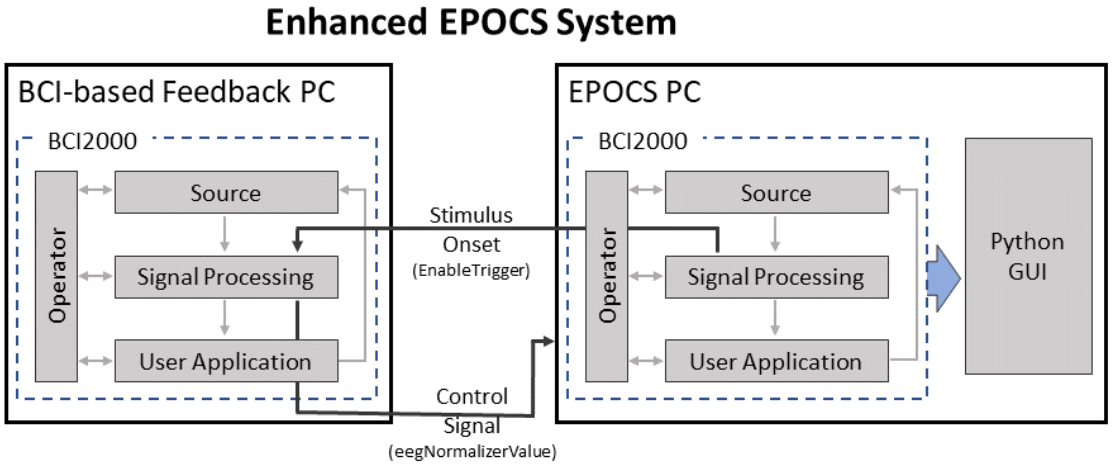


Figure 4.3: The enhanced setup consists of two different PCs, the BCI-based Feedback PC and the EPOCS PC connected to a LAN network. Both of them run BCI2000, but each one uses specially customized modules to handle different types of data (i.e., EEG and EMG). The two PCs exchange parameters/signals essential for the provided BCI-based feedback of SMRs to the participants (*eegNormalizerValue*) and for the synchronization of the data gathered from the two devices (*EnableTrigger*). The BCI2000 component of the EPOCS PC receives the (*eegNormalizerValue*) and it communicates it to the python GUI, where it is displayed to the participants.

The two instances of BCI2000 (running on different computers) were connected using a LAN with a UDP based transmission protocol. This allows them to exchange signal and parameter information. BCI2000 offers a specially designed interface for the realization of such connections called AppConnector. The BCI2000 AppConnector interface (i.e., external application interface) provides a bi-directional link allowing external processes to send and receive information. The type of information being transferred from one system to another can be states reflecting control signal data, or even set states to control the participant's task.

4.2.1. Synchronization of the Two Systems

The different nature of the paradigms carried by the two systems had be taken into account for their combination. The H-reflex operant conditioning task during conditioning trials can be considered a continuous task since no essential rest period is required for internal parameter updates (Figure 4.4). The participants are continually trying to alter the size of their reflexes without an explicit rest phase between each trial.

The SMR training protocol, on the other hand, has two phases; one "active" phase and one "rest" phase. During the active phase, the participant tries to control the cursor, as described in Chapter 3. During the rest phase, the participant relaxes (the screen in front of the participant is black). During the rest phase, the normalizer gains are updated. The normalizer applies a linear transformation to its input signal. The output of the normalizer is defined as:

$$output_i = (input_i - NormalizerOffset_i) \times NormalizerGain_i$$

where an offset value is subtracted from the input—each channel (index denoted with i)—, and the result multiplied with a gain value—the normalizer gain.

The normalizer uses buffers to store its past input based on buffer conditions given in the form of Boolean expressions. The current input will be transferred to the buffer only when the expression evaluates to true. Then the offset and the gain values are estimated from the normalizer based on the mean and variance of the buffer content so that the output signal has zero mean and unit variance. More precisely, the offset will be updated to the data mean, and the gain to the inverse square root of

the data variance. In other words, the system adapts to the participant, a concept that was mentioned previously (Figure 2.16).

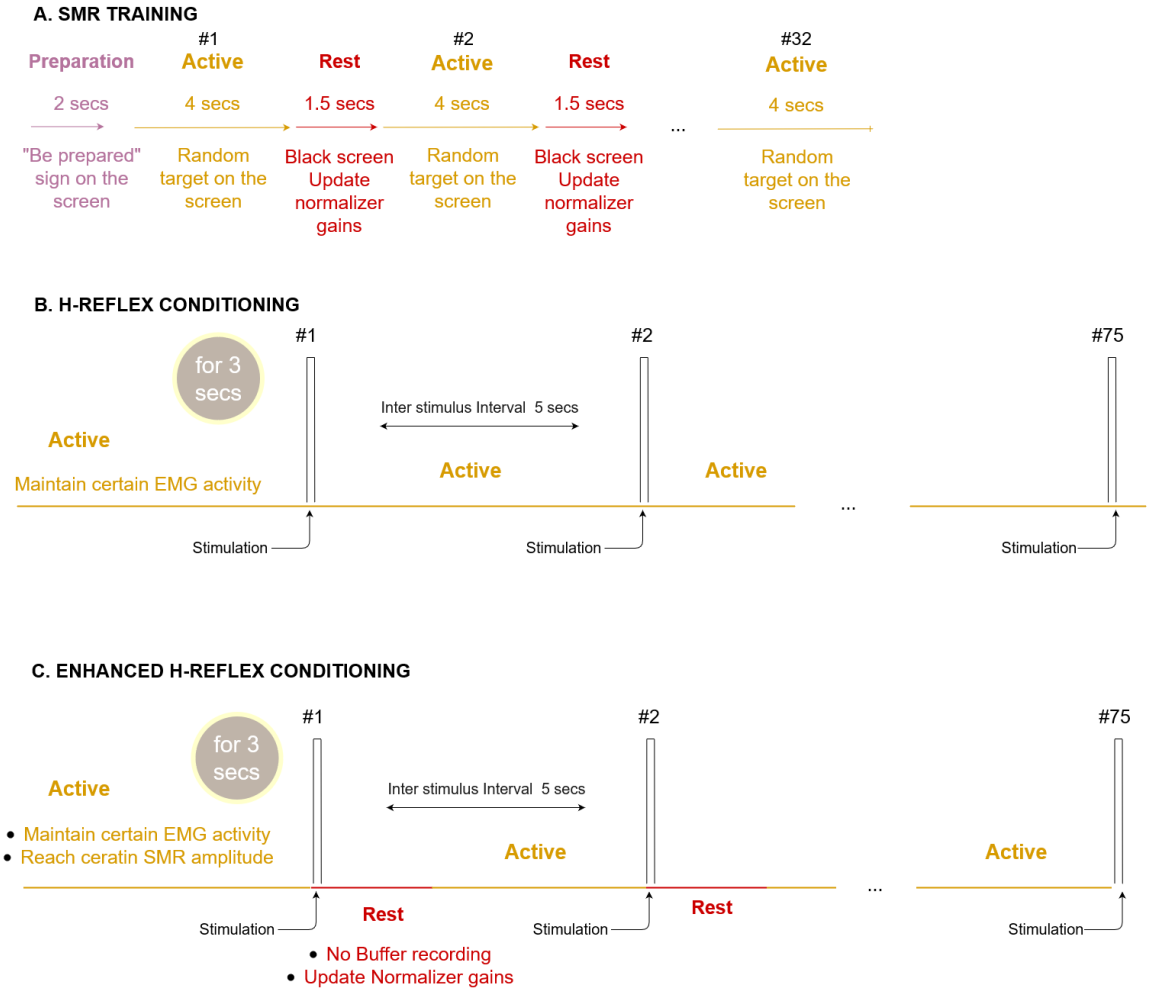


Figure 4.4: (The different nature of the tasks of SMR training, H-reflex conditioning, and enhanced H-reflex conditioning. A. During SMR training participants alternate between an active (yellow) and a rest phase(red) lasting 1.5 s. The rest phase is important for adaptation of the system to the user's performance (i.e., update of internal parameters) B. The task during the H-reflex conditioning consists of a constant active phase with no rest phase required by the system. An inter stimulus interval of five seconds is used to ensure the efficacy of the Ia-motoneurons synapses when they are evaluated after a previous activation. C. The task during the enhanced H-reflex conditioning needs to combine the logic of the SMR training and the H-reflex conditioning tasks. The active phase requires two prerequisites: to maintain EMG activity within a certain range and to reach a certain SMR amplitude value. If both of them are true then a stimulation is triggered followed by a rest phase that lasts ~ 2.5 s. During that phase internal parameters are updated.)

During the enhanced conditioning, the normalizer gains need to be updated in the same manner as during the SMR training (i.e., when the participant is resting). The enhanced conditioning needs to incorporate the rest phase of the SMR training into the continuous H-reflex operant conditioning procedure. Thus, the enhanced protocol is a hybrid procedure between the classic SMR training and the traditional H-reflex operant conditioning protocol. To implement that concept, the state *EnableTrigger* that reflects the timing of the stimulation was used. It is a Boolean state, meaning that it has the value zero when there is no stimulation and one when the stimulation begins. That parameter is sent back to BCI-based feedback PC, and it is used for the normalizer gains update.

On the BCI-based feedback PC, the *UpdateTrigger* parameter of BCI2000's standard normalizer

component was set to he following custom value (written in BCI2000's Expression syntax):

$$State(BlocksSinceLastTrigger) := EnableTrigger\ ?\ 0 : (State(BlocksSinceLastTrigger) + 1);$$
$$(State(BlocksSinceLastTrigger) > 0)\ \&\&\ (State(BlocksSinceLastTrigger) <= RestPeriod);$$

where
$RestPeriod = 0.25 * blocksPerSecond$
and
$blocksPerSecond = SamplingRate/SampleBlockSize$

This required a novel state variable called *BlocksSinceLastTrigger*, which was initialized in the script that launched BCI2000 on the BCI-based feedback PC.

The value of the *Updatetrigger* expression is Boolean as it gets the value one only during the rest phase for 2.5 s (with corresponds to the constant 0.25 in the expression). During the rest phase, no values are added to the buffer saving the SMR amplitude data, as artifacts due to the stimulation may occur during the stimulation until 2.50 sec afterwords. The state *BlocksSinceLastTrigger* is responsible for keeping track of the number of sample blocks that have passed. More specifically, the first row until the first semicolon, updates by one the state *BlocksSinceLastTrigger*, as long as the *Enable Trigger* is zero and resets it when *EnableTrigger* is one. The second row of the expression is the one that defines the final value of the *Updatetrigger* state to one, if the *BlocksSinceLastTrigger* state is greater than zero and smaller or equal to 250 ms calculated in sample blocks.

4.2.2. BCI-based Feedback Implementation

The BCI-based feedback was incorporated into the EPOCS python GUI. The enhanced GUI includes three bars. The first bar provides feedback on the amplitude of the muscle activity, and the third bar shows H-reflex size (Figure 4.5). The new addition is a middle bar that displays BCI-based feedback of SMRs generated by the BCI-based feedback PC. The shaded area of this new bar shows the amount of SMR amplitude required from the participant before a stimulation is triggered.

New functions at the GUI script written in python were added to define the placement of the new bar in the GUI, how the bar is updated, how the shaded area is defined, how it changes colors from red to green when the feedback value is within a specific predefined range, etc. Besides, the software component of EPOCS was customized to make triggering contingent on additional variables. Therefore, the triggering decision at the new version depends on EMG activation (as before) and BCI-based feedback of SMRs. When the former resides within the shaded region for at least three seconds, and the latter takes a value within the designated shaded area, nerve stimulation is triggered, and an H-reflex is elicited.

To implement this design, we updated the signal processing module of the BCI-based feedback PC. This Signal Processing module consists of filters for the feature selection, feature extraction, and feature translation as described in Chapter 3.1.5. These filters are connected in the form of a pipeline. The purpose of the signal processing module is to receive raw brain signals from the Source module, process them through the filter pipeline, and send the outcome (control signals) to the User Application module. The update included a new filter that was added after the last filter in the pipeline (the normalizer), called state transform filter. The purpose of this filter is to convert the control signals produced by the normalizer into states (a form that BCI2000 can send to external devices) so that the Python GUI of the EPOCS PC can display them to the middle bar. In Figure 4.3, the control signals are represented by the state *eegNormalizerValue* sent by BCI-based feedback PC to EPOCS PC to be displayed at from the python GUI. Therefore, the BCI2000 running on the EPOCS PC can receive the control signals and through the EPOCS python GUI, display them on the monitor seen by the participants.

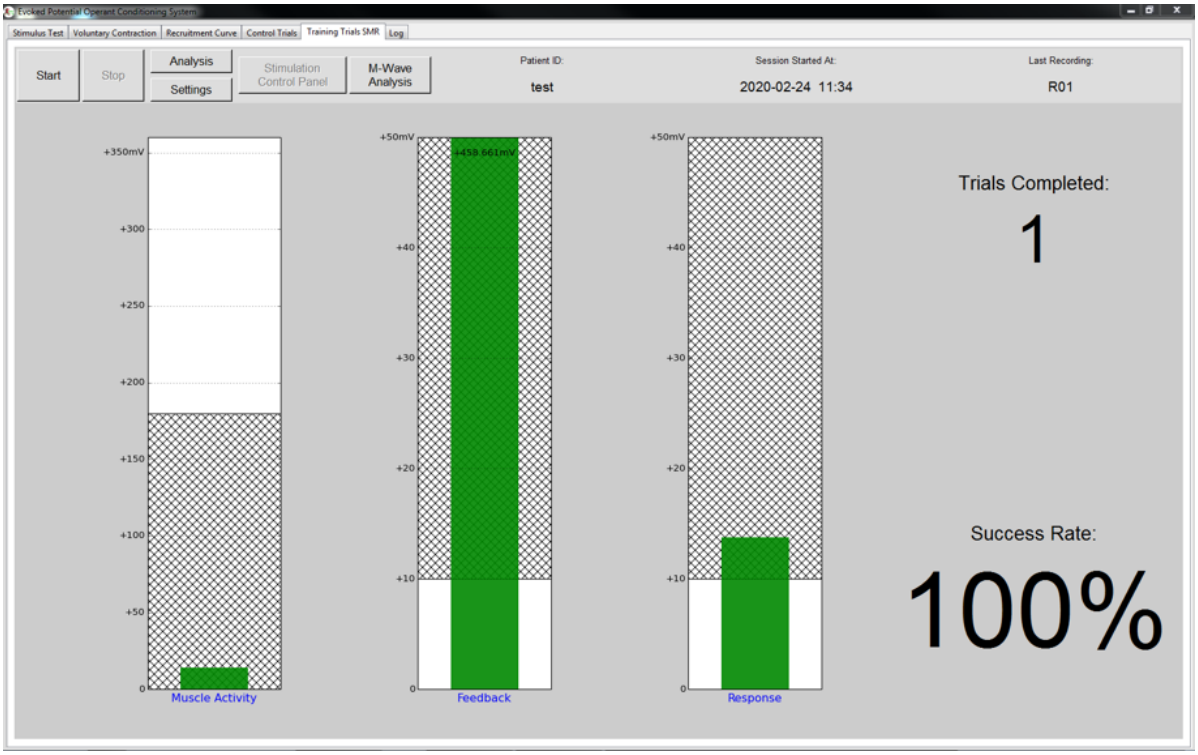


Figure 4.5: Graphical user interface of the enhanced EPOCS. The left-most bar indicates continuously-updated muscle activity that it is recorded with EMG. The middle bar shows real-time BCI-based feedback of SMRs to the participant. The third bar depicts the H-reflex response after stimulation. The shaded areas for the two feedback bars indicate the desired level muscle activity and SMR activity that the participant is expected to maintain for a specific time before the stimulation is elicited. For the response bar, the shaded area shows the desired size of H-reflex. When the bars are within the shaded areas, their color is green else they turn red. The y-axis of all the bars is in mV. Furthermore, the trials that have been completed and the current success rate are apparent to the participant.

5

Future work and Conclusions

5.1. Conclusions

It is well established that the central nervous system (CNS) exhibits plasticity throughout life, providing fertile ground from which to harvest new insights through experimental studies. This knowledge and the technological advancements that allow for interactions with the CNS have led to the creation of protocols that can induce beneficial CNS plasticity. These protocols can be used as additional rehabilitation options for people with neurological disorders.

The objective of this thesis was to increase the effectiveness of H-reflex operant conditioning protocol by incorporating BCI-based feedback of SMRs into the protocol. I hypothesize that the enhanced H-reflex operant conditioning system will increase the reliability, magnitude, and speed of the H-reflex operant conditioning. One of my goals was to test the performance of the enhanced protocol in healthy participants. Unfortunately, due to COVID-19, those experiments have been postponed. A prerequisite for using the enhanced H-reflex operant conditioning system is the ability of participants to voluntarily modulate their SMR recorded over the SMC. Therefore, before the suspension of human experiments in the US, participants were screened and SMR training was completed with five participants as part of their preparation to participate in the enhanced H-reflex operant conditioning protocol. Three out of five participants showed significant improvement of their SMR control after the training.

This project has several novel aspects. First, it is the first H-reflex operant conditioning system to provide guidance and feedback on SMRs to possibly increase the influence of plasticity starting in the SMC. Second, it is the first H-reflex conditioning system that provided real-time SMR feedback to the participants. Lastly, it was the first attempt to combine the existing neurotechnologies of SMR training and H-reflex operant conditioning in a single plasticity-inducing protocol.

Throughout the process of training the participants and combining the two systems, issues arose that had to be overcome. First, due to the substantial time commitment required by the study, only five of the original nine participants completed the SMR training. Second, the design of the integration and synchronization of the two systems had to be done appropriately to ensure that the proper concurrent function of them. These challenges were successfully addressed.

In conclusion, the current work serves as essential preliminary work for enhancing the H-reflex operant conditioning protocol. It also paves the way for further exploration of human neuronal networks, and potentially offers a way for people with motor disabilities to better perform activities of daily living.

5.2. Future Work

5.2.1. Description of the Enhanced H-reflex Operant Conditioning Protocol

The enhanced H-reflex operant conditioning protocol incorporates BCI-based feedback of SMRs into the H-reflex operant conditioning. The suggested procedure for the enhanced H-reflex operant conditioning protocol is described below.

The enhanced conditioning will include an optimization session, six baseline sessions, 24 conditioning sessions, and four follow-up sessions. Depending on the duration of the optimization session, the first baseline session can start on the same day as the optimization session, or on a different day. The

span of the conditioning is proposed to last for ten weeks, with three sessions per week per participant. According to the traditional H-reflex operant conditioning protocol, four follow-up sessions (15 days, one month, two months, and three months after the last conditioning session) are suggested to assess the persistence of changes in the size of the H-reflex.

To participate, individuals must have a measurable H-reflex (Chapter 2). Then, these participants should be trained to improve their ability to regulate their SMRs (Chapter 3). It may be possible eventually to incorporate this SMR-training process directly into the enhanced H-reflex operant conditioning paradigm.

After screening and training, stimulation and recording electrode placement should be optimized in preparation for the conditioning protocol. (In our experiments, we develop templates to help with consistent placement of electrodes across sessions (Chapter 2).) The optimization session starts with skin preparation (discussed in Chapter 2.1.1) and continues with the identification of the location of the electrodes on the skin where the maximum size of H-reflex can be measured with as low a stimulation current as possible. During the optimization session (as well as the baseline and training sessions) the participant's posture should be as consistent as possible.

The baseline, conditioning, and follow-up sessions should start with the selection of the appropriate cap size for each participant and EEG setup (as described in Chapters 2 and 3). During each session, a stimulation test should be used to confirm that the EPOCS system works as expected and to verify the correct electrode pad placement on the participant's right arm (EPOCS PC). Using BCI2000, the operator should inspect all the EEG channels and identify channels contaminated with noise (BCI-based feedback PC). The quality of signal acquisition from these channels can be enhanced with supplemental gel; if this fails to help, these channels should be excluded from the analysis. The impedance of the EEG electrodes should be less than 40 kΩ to maintain low-noise recordings.

In each session, the participant is asked to maintain a pre-specified level of muscle activation (i.e., ongoing EMG activity that remains within the background EMG limits). If they do this for a predetermined amount of time ($\sim$ 3 s) an H-reflex will be elicited. Following each stimulus, the current of the stimulator should be adjusted to maintain an M-wave of consistent size. The baseline sessions consist of 225 control trials. During those trials, participants will not be given any instructions related to the size of their H-reflex . After the baseline sessions have been completed, the conditioning sessions begin. Each conditioning session consists of 20 control trials followed by 225 conditioning trials. During the conditioning trials, the participants will be asked to increase or decrease the size of the H-reflex. Depending on the direction of the conditioning, the H-reflex should be larger or smaller than a criterion value. After each trial, participants will be given visual feedback that indicates whether they succeeded or failed to exceed the criterion. During the conditioning trials, participants will be given background muscle-activity and BCI-based SMR feedback. The background muscle activity should be kept within a specified range, and the BCI-based feedback of SMRs should meet specific criterion for the stimulation to occur. Thus, during conditioning trials, participants will try to change the size of their H-reflex while they receive two kinds of feedback on the screen (along with the outcome of the stimulation). During control trials, the participant will not be asked to modulate their SMRs or receive feedback on the size of their H-reflex..

The conditioning trials track the task-dependent adaptation phase of H-reflex operant conditioning [46]. The changes created by that influence will gradually create spinal cord plasticity. The control trials track the development of the long-term change of the H-reflex that occurs by influence from the CST. It has already been demonstrated that SMR modulation can give results equal in magnitude to the task-dependent adaptation [48]. SMR modulation during the H-reflex operant conditioning is also expected to have effects on the long-term change. One would expect these effects to be in support of the conditioning goals, but that must be proven with further experiments and investigation. This combination of protocols can shed light on brain sites and their recording features that contribute the most to the plasticity elicited by the reflex conditioning protocols. The preconditioning of the SMC through SMR training may facilitate the design of a more robust protocol that targets specific critical sites of the CNS. Localization of specific features before the SMR training, depending on each patient's need, could provide further improvement to the reflex protocol (i.e., the increase of the magnitude and the speed of the reflex conditioning). The combination of protocols could be beneficial regardless of the choice of the muscle to be conditioned.

5.2.2. Improvements

Further improvements in the experimental setup could be made during future studies when performing the SMR training and the enhanced conditioning. First, a surveillance system could be implemented that would provide the operator so with a visual display of the participant's face and body. It is common during the beginning of the training that participants make facial expressions when trying to move the cursor on the screen in front of them. This produces EMG artifacts from facial muscles in the EEG recordings. As people tend to do those expressions unconsciously, it is the operator's task to spot them and advise the participants to relax. Similarly, some participants (including the neurologically unimpaired) make small movements (either unconsciously or due to misunderstanding the instructions) that can induce artifacts. With the aid of the surveillance system, the operator can watch for these movements without interrupting the ongoing training and, after each run, make the participants aware of their actions to help them perform properly during the training.

Second, during the H-reflex operant conditioning, participants need to reproduce the same posture within and between sessions to the greatest extent possible. Therefore, a system for identifying body (and particularly arm) positioning would improve the stability of H-reflex recordings and, presumably, the efficacy of the H-reflex operant conditioning protocol. Such a system could be based on indoor positioning technology, including wearable receiving tags at crucial points of the human body and a distance measurement method with ultra-wideband (UWB) radio to identify crucial points [18].

Lastly, NCAN has already envisioned making the conditioning process more appealing by gamification of the process. Motivation is a crucial factor for learning [21]. Acquisition of SMR control and operant conditioning-induced H-reflex change represent the learning new skills. Whether the training is used for research or rehabilitation, it is expected that gamification will improve the performance of the participants by increasing their engagement with the task.

Bibliography

[1] Bci2000 wiki. *BCI2000 Wiki*. URL `https://www.bci2000.org/mediawiki/index.php/Main_Page`.

[2] Jeremy Andrew Bamford and Scott Francis Davis. The h-reflex and f-response. In *Principles of Neurophysiological Assessment, Mapping, and Monitoring*, pages 171–179. Springer, 2020.

[3] Chadwick B Boulay, Xiang Yang Chen, and Jonathan R Wolpaw. Electrocorticographic activity over sensorimotor cortex and motor function in awake behaving rats. *Journal of neurophysiology*, 113(7):2232–2241, 2015.

[4] David Burke. Clinical uses of h reflexes of upper and lower limb muscles. *Clinical neurophysiology practice*, 1:9–17, 2016.

[5] Charles Capaday. Neurophysiological methods for studies of the motor system in freely moving human subjects. *Journal of neuroscience methods*, 74(2):201–218, 1997.

[6] Xiang Yang Chen and Jonathan R Wolpaw. Dorsal column but not lateral column transection prevents down-conditioning of h reflex in rats. *Journal of neurophysiology*, 78(3):1730–1734, 1997.

[7] Xiang Yang Chen and Jonathan R Wolpaw. Probable corticospinal tract control of spinal cord plasticity in the rat. *Journal of Neurophysiology*, 87(2):645–652, 2002.

[8] Xiang Yang Chen and Jonathan R Wolpaw. Ablation of cerebellar nuclei prevents h-reflex down-conditioning in rats. *Learning & Memory*, 12(3):248–254, 2005.

[9] Xiang Yang Chen, Jonathan S Carp, Lu Chen, and Jonathan R Wolpaw. Corticospinal tract transection prevents operantly conditioned h-reflex increase in rats. *Experimental brain research*, 144 (1):88–94, 2002.

[10] Xiang Yang Chen, Jonathan S Carp, Lu Chen, and Jonathan R Wolpaw. Sensorimotor cortex ablation prevents h-reflex up-conditioning and causes a paradoxical response to down-conditioning in rats. *Journal of neurophysiology*, 96(1):119–127, 2006.

[11] Xiang Yang Chen, Yu Wang, Yi Chen, Lu Chen, and Jonathan R Wolpaw. The inferior olive is essential for long-term maintenance of a simple motor skill. *Journal of neurophysiology*, 116(4): 1946–1955, 2016.

[12] Yi Chen, Yu Wang, Lu Chen, Chenyou Sun, Arthur W English, Jonathan R Wolpaw, and Xiang Yang Chen. H-reflex up-conditioning encourages recovery of emg activity and h-reflexes after sciatic nerve transection and repair in rats. *Journal of Neuroscience*, 30(48):16128–16136, 2010.

[13] Mar Cortes, Ana Heloisa Medeiros, Aasta Gandhi, Peter Lee, Hermano Igo Krebs, Gary Thickbroom, and Dylan Edwards. Improved grasp function with transcranial direct current stimulation in chronic spinal cord injury. *NeuroRehabilitation*, 41(1):51–59, 2017.

[14] Numa Dancause, Sylvie Nadeau, and Serge Rossignol. *Sensorimotor rehabilitation: At the crossroads of basic and clinical sciences*. Elsevier, 2015.

[15] Amir Eftekhar, James JS Norton, Christine M McDonough, and Jonathan R Wolpaw. Retraining reflexes: clinical translation of spinal reflex operant conditioning. *Neurotherapeutics*, 15(3):669–683, 2018.

[16] ML Evatt, SL Wolf, and RL Segal. Modification of human spinal stretch reflexes: preliminary studies. *Neuroscience letters*, 105(3):350–355, 1989.

[17] P HOFFMANN. Beitrage zur kenntnis der menschlichen reflex emit besonderer berucksichtigung der elektrichen. erscheinnungen. *Arch-Physol*, 1910.

[18] Xiaoping Huang, Fei Wang, Jian Zhang, Zelin Hu, and Jian Jin. A posture recognition method based on indoor positioning technology. *Sensors*, 19(6):1464, 2019.

[19] William James. *The principles of psychology*, volume 1. Cosimo, Inc., 2007.

[20] Florence Peterson Kendall, Elizabeth Kendall McCreary, Patricia Geise Provance, Mary Rodgers, William Anthony Romani, et al. *Muscles, testing and function: with posture and pain*, volume 103. Williams & Wilkins Baltimore, MD, 1993.

[21] Gabriela Kiryakova, Nadezhda Angelova, and Lina Yordanova. Gamification in education. Proceedings of 9th International Balkan Education and Science Conference, 2014.

[22] Jerzy Konorski. Conditioned reflexes and neuron organization. 1948.

[23] Lisa Koski, Thomas J Mernar, and Bruce H Dobkin. Immediate and long-term changes in corticomotor output in response to rehabilitation: correlation with functional improvements in chronic stroke. *Neurorehabilitation and neural repair*, 18(4):230–249, 2004.

[24] Dennis J McFarland, Lynn M McCane, Stephen V David, and Jonathan R Wolpaw. Spatial filter selection for eeg-based communication. *Electroencephalography and clinical Neurophysiology*, 103(3):386–394, 1997.

[25] Dennis J McFarland, William A Sarnacki, Theresa M Vaughan, and Jonathan R Wolpaw. Brain-computer interface (bci) operation: signal and noise during early training sessions. *Clinical neurophysiology*, 116(1):56–62, 2005.

[26] Dennis J McFarland, Dean J Krusienski, and Jonathan R Wolpaw. Brain–computer interface signal processing at the wadsworth center: mu and sensorimotor beta rhythms. *Progress in brain research*, 159:411–419, 2006.

[27] Dennis J McFarland, William A Sarnacki, and Jonathan R Wolpaw. Should the parameters of a bci translation algorithm be continually adapted? *Journal of neuroscience methods*, 199(1):103–107, 2011.

[28] Christa Neuper and Gert Pfurtscheller. Evidence for distinct beta resonance frequencies in human eeg related to specific sensorimotor cortical areas. *Clinical Neurophysiology*, 112(11):2084–2097, 2001.

[29] Ernst Niedermeyer. *Niedermeyer's electroencephalography: basic principles, clinical applications, and related fields*. Lippincott Williams & Wilkins, 2011.

[30] G Pfurtscheller. Functional topography during sensorimotor activation studied with event-related desynchronization mapping. *Journal of clinical neurophysiology: official publication of the American Electroencephalographic Society*, 6(1):75–84, 1989.

[31] Gert Pfurtscheller. Event-related synchronization (ers): an electrophysiological correlate of cortical areas at rest. *Electroencephalography and clinical neurophysiology*, 83(1):62–69, 1992.

[32] Gert Pfurtscheller and Fernando Lopes Da Silva. Eeg-event-related desynchronization (erd) and event-related synchronization. In *Electroencephalography-Basic Principles, Clinical Applications and Related Fields.*, pages 935–948. Kluwer/Lippincott Williams & Wilkins, 2011.

[33] GERT PFURTSCHELLER and Dennis J McFarland. 13| bcis that use sensorimotor rhythms. *Brain-computer interfaces: principles and practice*, page 227, 2012.

[34] Gert Pfurtscheller and Christa Neuper. Event-related synchronization of mu rhythm in the eeg over the cortical hand area in man. *Neuroscience letters*, 174(1):93–96, 1994.

[35] Gert Pfurtscheller and Christa Neuper. Dynamics of sensorimotor oscillations in a motor task. In *Brain-Computer Interfaces*, pages 47–64. Springer, 2009.

[36] Gert Pfurtscheller, Clemens Brunner, Alois Schlögl, and FH Lopes Da Silva. Mu rhythm (de) synchronization and eeg single-trial classification of different motor imagery tasks. *NeuroImage*, 31(1):153–159, 2006.

[37] Emmanuel Pierrot-Deseilligny and David Burke. *The circuitry of the human spinal cord: spinal and corticospinal mechanisms of movement*. Cambridge University Press, 2012.

[38] Serge Rossignol and Alain Frigon. Recovery of locomotion after spinal cord injury: some facts and mechanisms. *Annual review of neuroscience*, 34:413–440, 2011.

[39] Mohamed A Sabbahi and Edward Michael Sedgwick. Age-related changes in monosynaptic reflex excitability. *Journal of gerontology*, 37(1):24–32, 1982.

[40] Gerwin Schalk, Dennis J McFarland, Thilo Hinterberger, Niels Birbaumer, and Jonathan R Wolpaw. Bci2000: a general-purpose brain-computer interface (bci) system. *IEEE Transactions on biomedical engineering*, 51(6):1034–1043, 2004.

[41] Cyril Schneider and Charles Capaday. Progressive adaptation of the soleus h-reflex with daily training at walking backward. *Journal of neurophysiology*, 89(2):648–656, 2003.

[42] Eric W Sellers, Dennis J McFarland, Theresa M Vaughan, and Jonathan R Wolpaw. Bcis in the laboratory and at home: the wadsworth research program. In *Brain-Computer Interfaces*, pages 97–111. Springer, 2009.

[43] H Sheikh, DJ McFarland, WA Sarnacki, and JR Wolpaw. Eeg-based communication: Characterizing eeg control and performance relationship. *Neurosci. Lett*, 345:89–92, 2003.

[44] R Srinivasan. Acquiring brain signals from outside the brain. *Brain-computer interfaces: Principles and practice*, 6:105–122, 2012.

[45] Sarah L Thomas and Monica A Gorassini. Increases in corticospinal tract function by treadmill training after incomplete spinal cord injury. *Journal of neurophysiology*, 94(4):2844–2855, 2005.

[46] Aiko K Thompson, Xiang Yang Chen, and Jonathan R Wolpaw. Acquisition of a simple motor skill: task-dependent adaptation plus long-term change in the human soleus h-reflex. *Journal of Neuroscience*, 29(18):5784–5792, 2009.

[47] Aiko K Thompson, Ferne R Pomerantz, and Jonathan R Wolpaw. Operant conditioning of a spinal reflex can improve locomotion after spinal cord injury in humans. *Journal of Neuroscience*, 33(6): 2365–2375, 2013.

[48] Aiko K Thompson, Hannah Carruth, Rachel Haywood, N Jeremy Hill, William A Sarnacki, Lynn M McCane, Jonathan R Wolpaw, and Dennis J McFarland. Effects of sensorimotor rhythm modulation on the human flexor carpi radialis h-reflex. *Frontiers in neuroscience*, 12:505, 2018.

[49] Mark H Trimble. Postural modulation of the segmental reflex: effect of body tilt and postural sway. *International journal of neuroscience*, 95(1-2):85–100, 1998.

[50] Kylie J Tucker, Meltem Tuncer, and Kemal S Türker. A review of the h-reflex and m-wave in the human triceps surae. *Human movement science*, 24(5-6):667–688, 2005.

[51] Jonathan R Wolpaw. What can the spinal cord teach us about learning and memory? *The Neuroscientist*, 16(5):532–549, 2010.

[52] Jonathan R Wolpaw. The negotiated equilibrium model of spinal cord function. *The Journal of physiology*, 596(16):3469–3491, 2018.

[53] Jonathan R Wolpaw and Chadwick B Boulay. Brain signals for brain–computer interfaces. In *Brain-computer interfaces*, pages 29–46. Springer, 2009.

[54] Jonathan R Wolpaw and Xiang Yang Chen. The cerebellum in maintenance of a motor skill: a hierarchy of brain and spinal cord plasticity underlies h-reflex conditioning. *Learning & memory*, 13(2):208–215, 2006.

[55] JONATHAN R Wolpaw and JULIE A O'Keefe. Adaptive plasticity in the primate spinal stretch reflex: evidence for a two-phase process. *Journal of Neuroscience*, 4(11):2718–2724, 1984.

[56] Jonathan R Wolpaw and Ann M Tennissen. Activity-dependent spinal cord plasticity in health and disease. *Annual review of neuroscience*, 24(1):807–843, 2001.

[57] Jonathan R Wolpaw and Elizabeth W Wolpaw. Brain-computer interfaces: something new under the sun. *Brain-computer interfaces: principles and practice*, 14, 2012.

[58] Jonathan R Wolpaw, Victor A Kieffer, Richard F Seegal, David J Braitman, and Michael G Sanders. Adaptive plasticity in the spinal stretch reflex. *Brain research*, 267(1):196–200, 1983.

[59] Jonathan R Wolpaw, Dennis J McFarland, Gregory W Neat, and Catherine A Forneris. An eeg-based brain-computer interface for cursor control. *Electroencephalography and clinical neurophysiology*, 78(3):252–259, 1991.

[60] Jonathan R Wolpaw, Patricia A Herchenroder, and Jonathan S Carp. Operant conditioning of the primate h-reflex: factors affecting the magnitude of change. *Experimental brain research*, 97(1): 31–39, 1993.

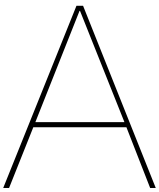
[61] Jonathan R Wolpaw, Niels Birbaumer, Dennis J McFarland, Gert Pfurtscheller, and Theresa M Vaughan. Brain–computer interfaces for communication and control. *Clinical neurophysiology*, 113(6):767–791, 2002.

[62] Jonathan R Wolpaw, Dennis J McFarland, Theresa M Vaughan, and Gerwin Schalk. The wadsworth center brain-computer interface (bci) research and development program. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 11(2):1–4, 2003.

[63] JR Wolpaw. Spinal cord plasticity in acquisition and maintenance of motor skills. *Acta Physiologica*, 189(2):155–169, 2007.

[64] JF Yang, J Fung, M Edamura, R Blunt, RB Stein, and H Barbeau. H-reflex modulation during walking in spastic paretic subjects. *Canadian Journal of Neurological Sciences*, 18(4):443–452, 1991.

[65] Paul E Zehr. Considerations for use of the hoffmann reflex in exercise studies. *European journal of applied physiology*, 86(6):455–468, 2002.



Appendix - Questionnaires

Subject ID_____ **Date**_____

Activity Questionnaire

Please place an X in the box that best describes your level of participation in the following activities:
Rarely: I have never done this or I have only done this a few times in my life
Occasionally: I have done this more than a few times or I participate in this off and on
Often: I have done this many times in the past or currently on a regular basis

Activity	Rarely	Occasionally	Often	Comments
Archery				
Ball-over-net sports (e.g. badminton, volleyball, ping pong, tennis etc.)				
Basketball				
Bat-and-ball sports (e.g. baseball/softball, cricket, etc.)				
Billiards/Pool				
Bowling				
Boxing				
Calligraphy				
Canoeing/Kayaking				
Chess				
Climbing (e.g. rock, ice, etc.)				
Crossfit				
Cycling				
Dance, please specify (e.g. modern, ballet, ballroom, etc.)				
Darts				
Disc golf/Frisbee				
Diving				
Drawing				

Activity	Rarely	Occasionally	Often	Comments
Equine sports (e.g. dressage, racing, recreational riding)				
Fencing				
Fishing				
Football/Rugby				
Golf				
Gymnastics				
Handball				
Hiking				
Hockey, please specify (e.g. field, ice, etc.)				
Juggling				
Lacrosse				
Martial Arts				
Meditation				
Motor sports, please specify (e.g.auto/boat racing, motorcycle, dirt bike, etc.)				
Orienteering				
Paint ball				
Painting (artistic)				
Polo				
Racquetball/Squash				
Rowing/Crew				
Running (other than track events)				
Sailing				
Skating, please specify (e.g., roller, ice, etc)				
Skateboarding				

Activity	Rarely	Occasionally	Often	Comments
Sking, please specify (e.g. alpine, nordic, jumping, etc.)				
Sled sports (e.g. bobsled, luge, etc.)				
Snowboarding				
Soccer				
Stand-up paddleboarding				
Swimming				
Surfing (including windsurfing)				
Tai Chi				
Target shooting/Skeet				
Track and Field, please specify events				
Video games				
Video games with a joystick				
Water polo				
Weightlifting				
Wrestling				
Yoga				

Please list below other sports or activities that you participate in regularly.

Subject ID_____ **Date**_____

EDINBURGH HANDEDNESS INVENTORY

Instructions (to be read by the examiner):

Please indicate your preferences in the use of hands in the following activities by indicating the most appropriate response. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, indicate 'Always'; otherwise indicate 'Usually'. If in any case you are indifferent, indicate 'Indifferent'. Please do not simply indicate one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate response. *[Only if participant has had a stroke: Indicate the preferences you would have had before you were affected by the stroke.]* Answer all the questions; only leave blank if you have no experience at all with the object or task.

TASK / OBJECT	**Always Left**	**Usually Left**	**Indifferent**	**Usually Right**	**Always Right**
1. Writing	AL	UL	I	UR	AR
2. Drawing	AL	UL	I	UR	AR
3. Throwing	AL	UL	I	UR	AR
4. Using scissors	AL	UL	I	UR	AR
5. Brushing teeth	AL	UL	I	UR	AR
6. Using a knife (without fork)	AL	UL	I	UR	AR
7. Using a spoon	AL	UL	I	UR	AR
8. Sweeping a broom (upper hand)	AL	UL	I	UR	AR
9. Striking a match (match)	AL	UL	I	UR	AR
10 Opening a box (lid)	AL	UL	I	UR	AR
	LQ =				

Subject ID_____ **Date**_____

Adapted from: Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia *1971 9: 97-113.*

SCORING THE EHI:

1. Sum the number of AL responses and multiply by -2 _____ (1)
2. Sum the number of UL responses and multiply by -1 _____ (2)
3. Sum the number of AR responses and multiply by 2 _____ (3)
4. Sum the number of UR responses and multiply by 1 _____ (4)

5. Sum the 4 values above _____ (A)
6. Sum the absolute values of the 4 values above _____ (B)

7. Calculate A / B * 100 Hand LQ = _____ % (range: -100 to +100%)

Subject ID_____ **Date**_____

Subject Demographics and Health History

1. **Gender** (Please select one)**:** _____ Female _____ Male

2. **Ethnicity** (Please **select only one response**)**:** Do you consider yourself to be Hispanic or Latino?

   That is a person of Mexican, Puerto Rican, Cuban, South or Central American, or other Spanish culture or origin, regardless of race. The term "Spanish origin" can be used in addition to "Hispanic" or "Latino".

   _____ Hispanic or Latino

   _____ Not Hispanic or Latino

   _____ Prefer Not to Respond

3. **Race** (Please select **one or more responses**)**:** What race do you consider yourself to be?

   a. A person having origins in any of the original peoples of North, Central, or South America, and who maintains tribal affiliation or community attachment.

      _____ American Indian or Alaska Native

   b. A person having origins in any of the original peoples of the Far East, Southeast Asia, or the Indian subcontinent, including, for example, Cambodia, China, India, Japan, Korea, Malaysia, Pakistan, the Philippine Islands, Thailand, and Vietnam.

      _____ Asian

   c. A person having origins in any of the original peoples of Hawaii, Guam, Samoa, or other Pacific Islands.

      _____ Native Hawaiian or Other Pacific Islander

   d. A person having origins in any of the black racial groups of Africa.

      _____ Black or African American

   e. A person having origins in any of the original peoples of Europe, the Middle East, or North Africa.

      _____ White

   f. Please put a check in the space below if you prefer not to identify your race.

      _____ Prefer Not to Respond

Subject ID_____ **Date**_____

4. Age: _____ Date of Birth: _____ Education Level: _____

5. Height: _____ Weight: _____

6. Leg Length: Right _____ Left _____

Arm Length: Right _____ Left _____

7. Have you ever been diagnosed with a neurological disorder? _____

If no, skip to question **8**. If yes, please answer the following:

a. What is your diagnosis?

b. At what age were you first diagnosed?

c. At what age did you notice symptoms?

d. How does this diagnosis currently affect your movement?

8. Have you ever been diagnosed with an anxiety related condition? _____

9. Have you ever injured, or had surgery on, your head, spinal cord, back, neck, legs, arms, feet or hands? If so, please specify the location(s) and describe:

10. Have you had any problems with balance, dizziness or fainting in the past 6 months? _____

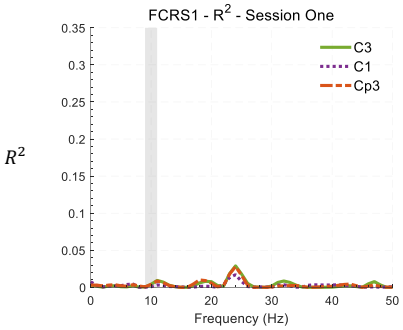
11. Are you taking any medications? _____ If yes, please list:

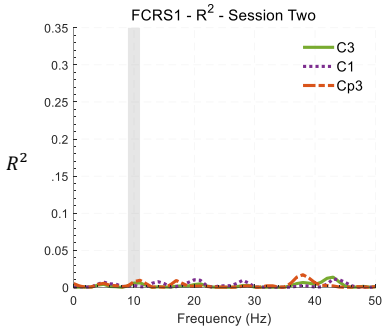
12. How many hours of physical activity do you get per week (on average)? _____

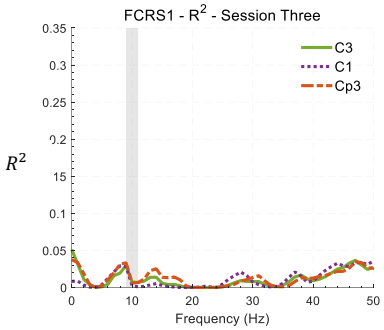
B

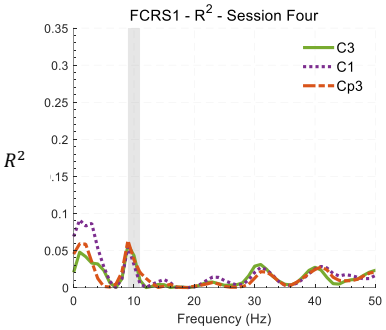
Appendix - SMR Training Feature Plots

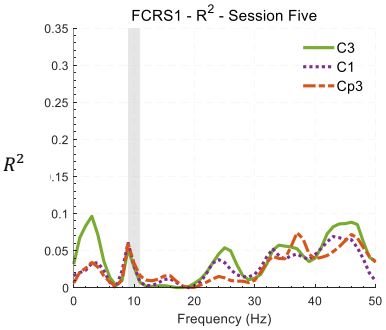
FCRS1 SMR Training Sessions – Feature Plots

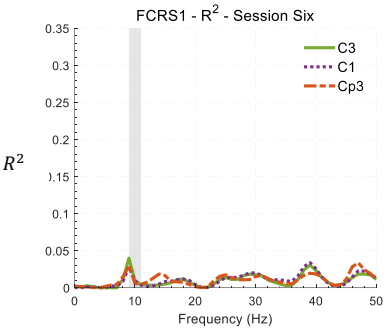


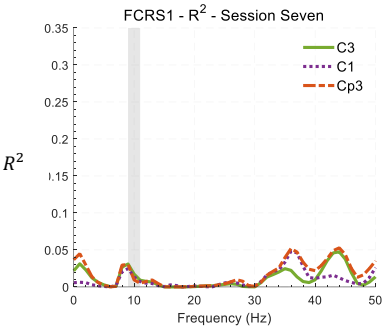


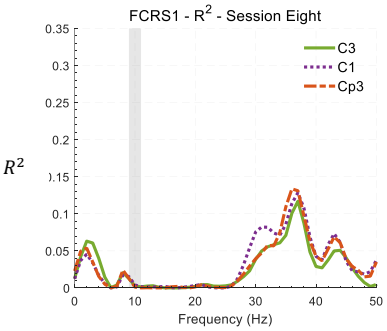


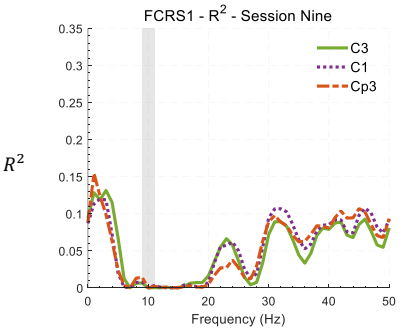


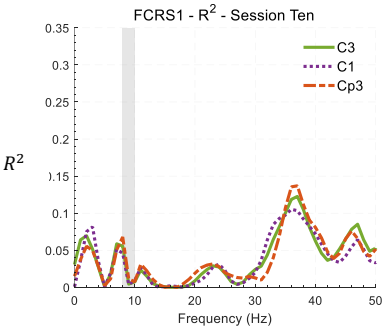


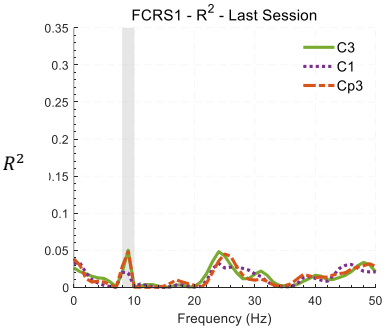




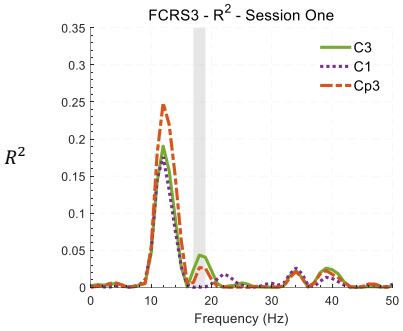


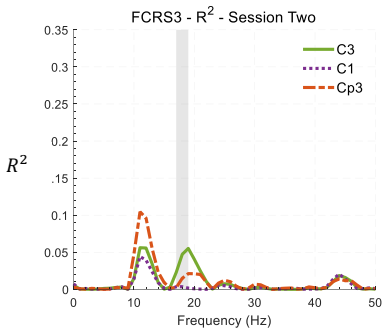


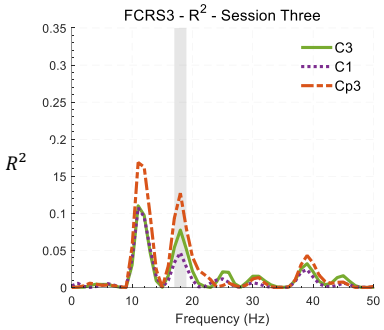


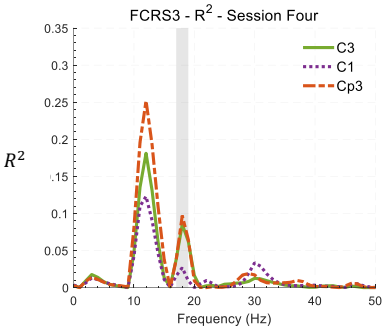


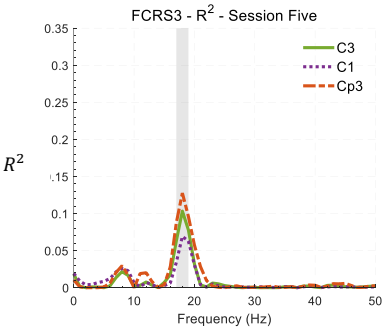
FCRS3 SMR Training Sessions – Feature Plots

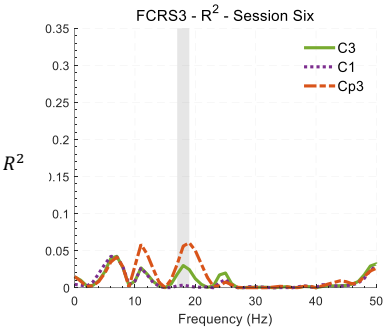


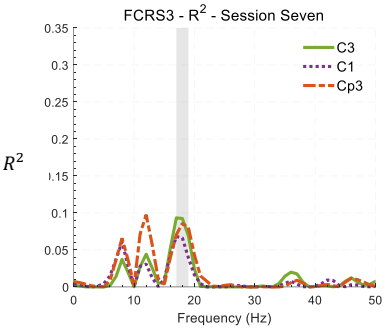


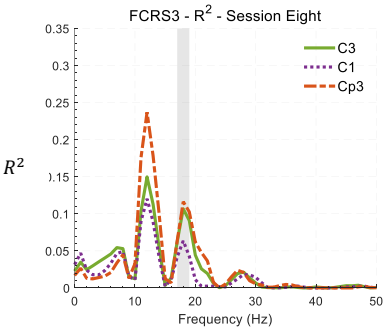


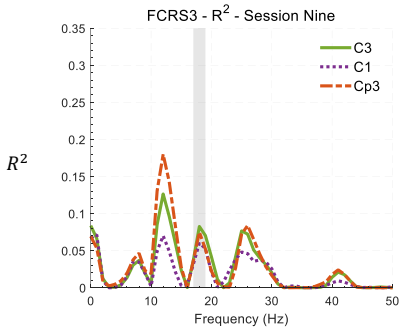


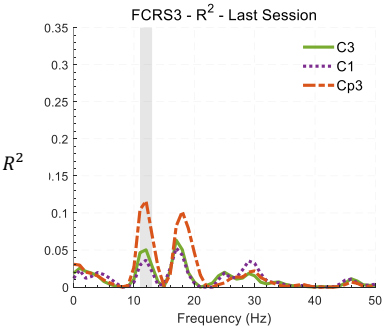




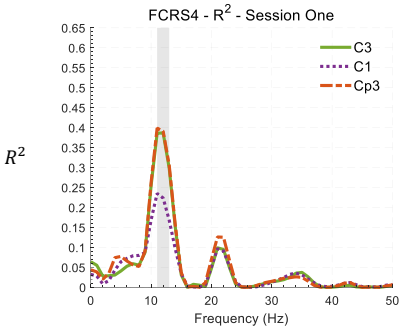


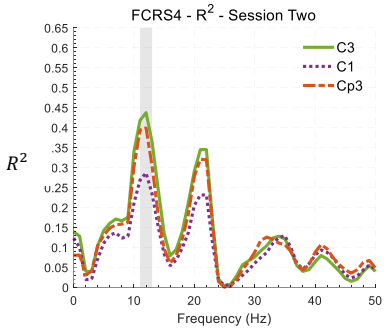


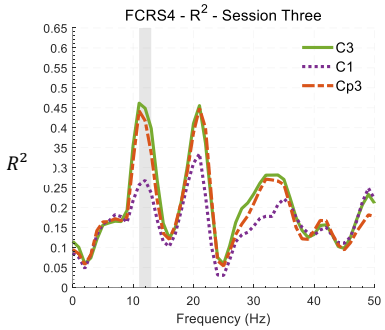


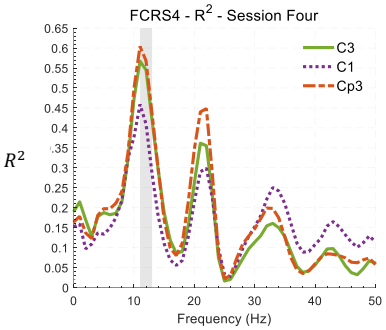


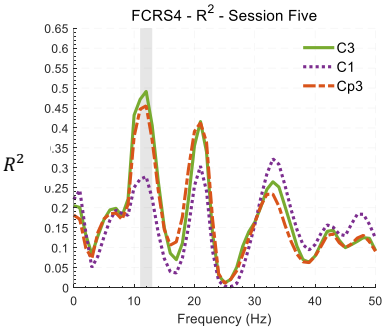
FCRS4 SMR Training Sessions – Feature Plots

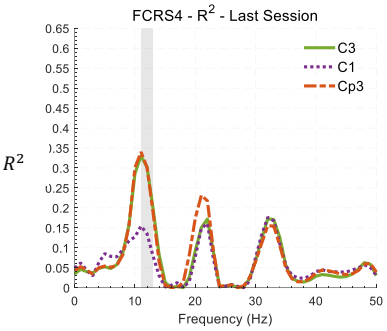




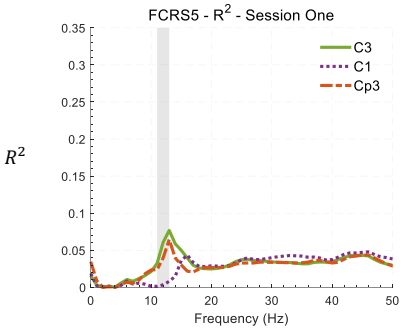


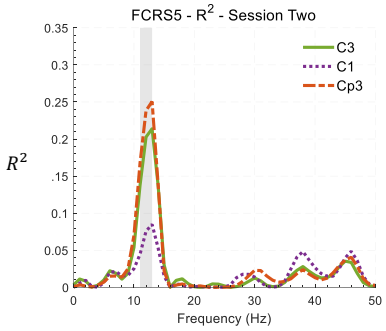


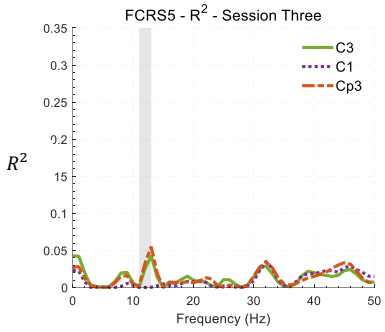


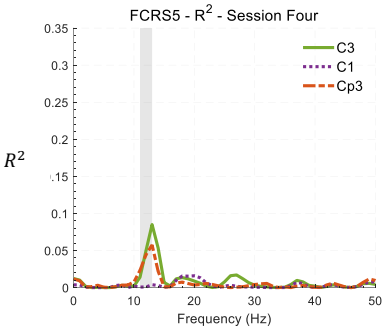


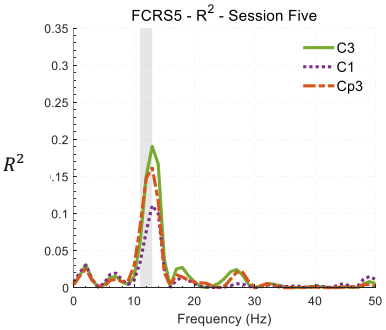
FCRS5 SMR Training Sessions – Feature Plots

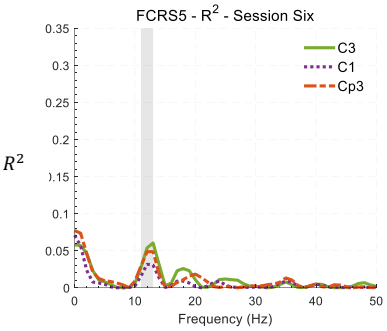


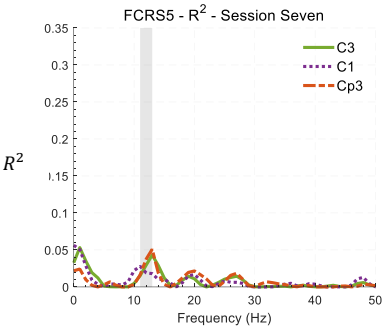


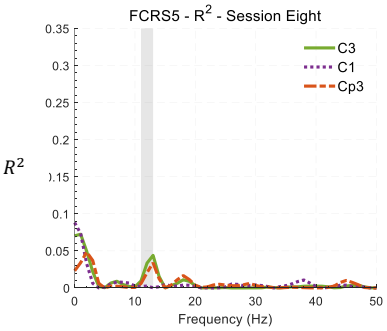


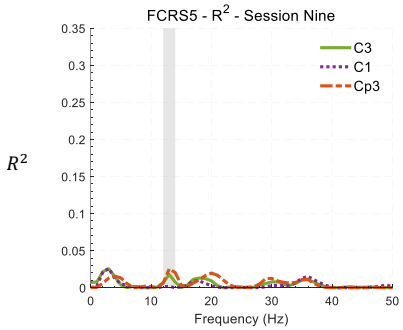


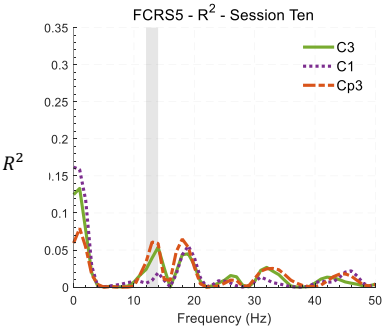




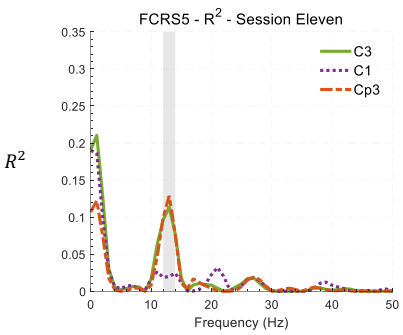


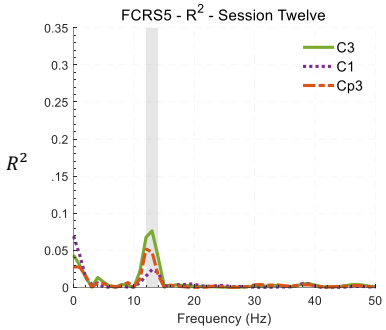


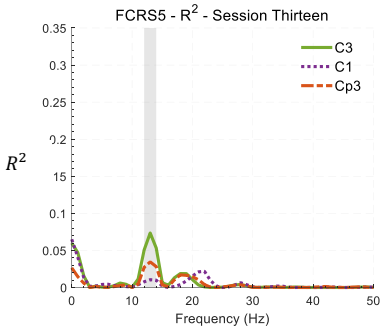


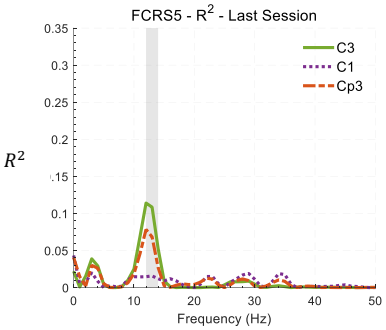


FCRS5 SMR Training Sessions – Feature Plots

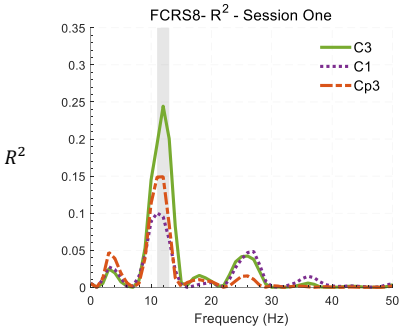


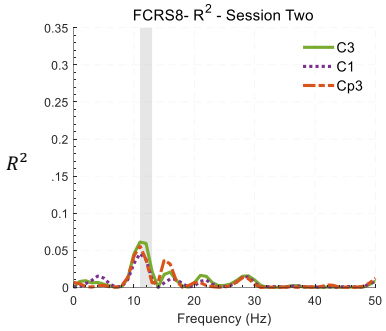


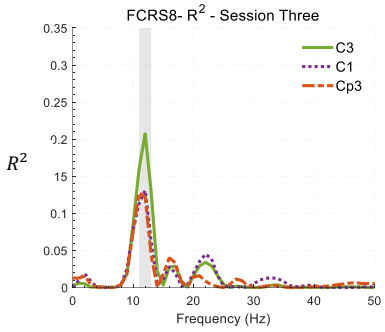


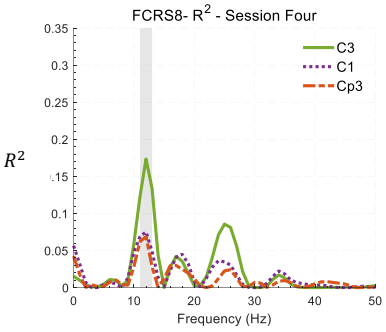


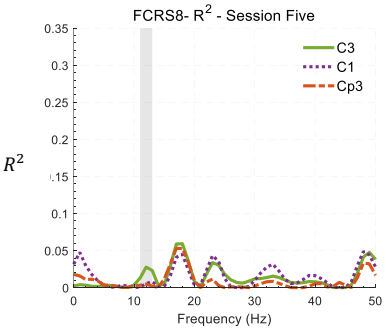
FCRS8 SMR Training Sessions – Feature Plots

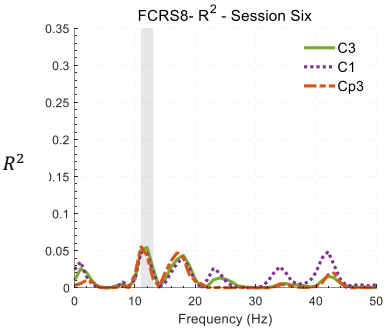


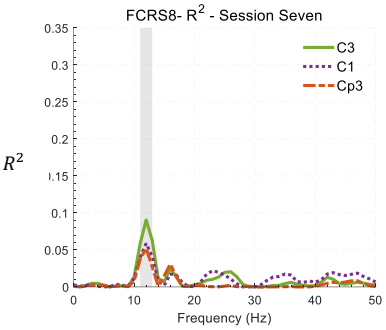


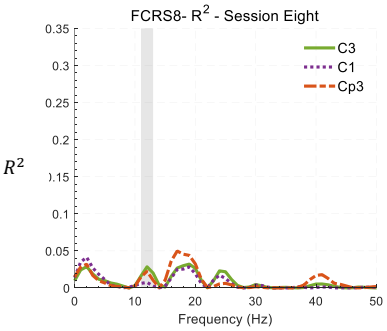


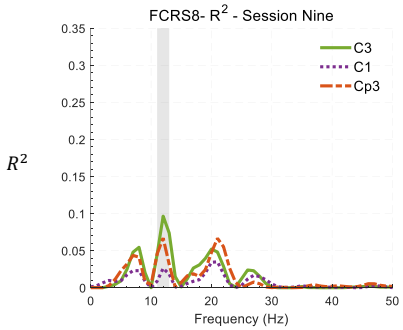


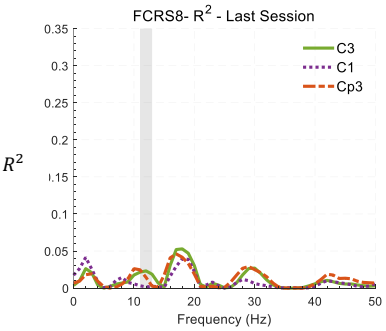




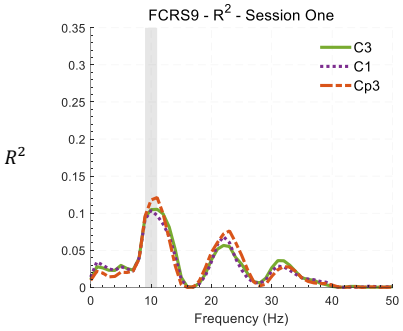


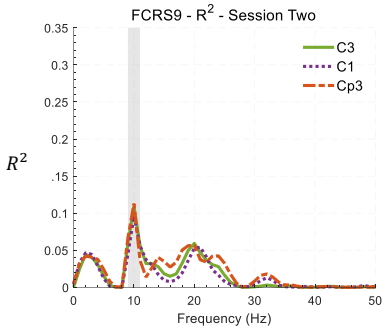


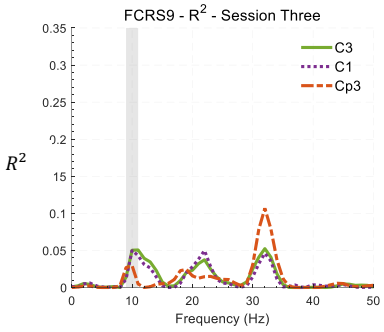


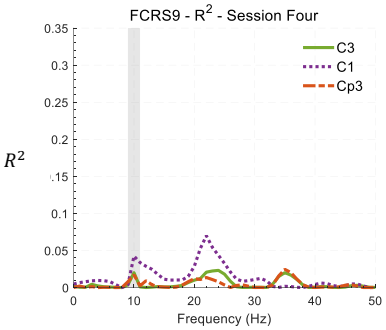


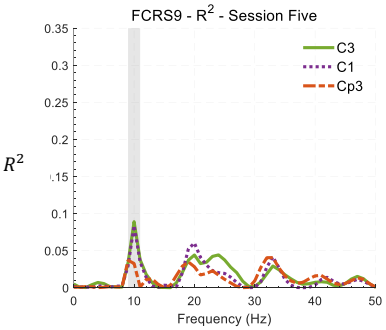
FCRS9 SMR Training Sessions – Feature Plots

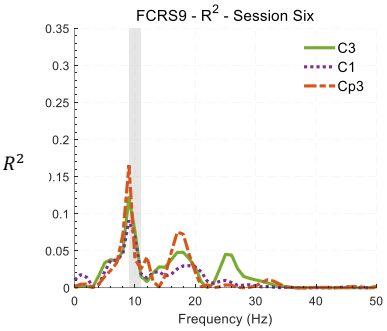


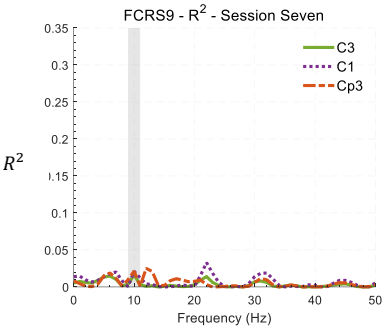


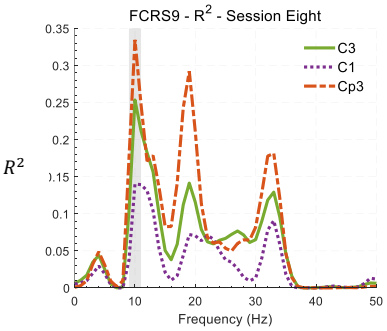


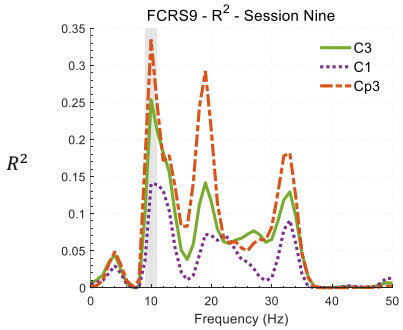


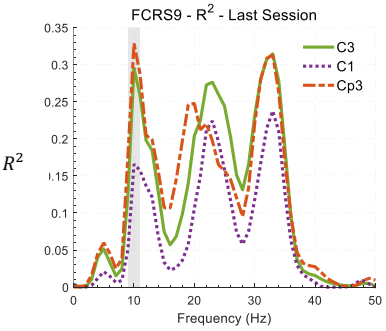












C

Appendix - Statistical Analysis with SPSS

```
FCRS1
EXAMINE VARIABLES=Session2 Session11
  /PLOT BOXPLOT HISTOGRAM NPPLOT
  /COMPARE GROUPS
  /STATISTICS DESCRIPTIVES EXTREME
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.
```

Explore

Notes

Output Created		18-JUL-2020 11:11:37
Comments		
Input	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	8
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.

Syntax		EXAMINE VARIABLES=Session2 Session11 /PLOT BOXPLOT HISTOGRAM NPPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE /NOTOTAL.
Resources	Processor Time	00:00:04.02
	Elapsed Time	00:00:01.80

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Session2	8	100.0%	0	0.0%	8	100.0%
Session11	8	100.0%	0	0.0%	8	100.0%

Descriptives

			Statistic	Std. Error
Session2	Mean		18.5000	1.03510
	95% Confidence Interval for Mean	Lower Bound	16.0524	
		Upper Bound	20.9476	
	5% Trimmed Mean		18.4444	
	Median		18.0000	
	Variance		8.571	
	Std. Deviation		2.92770	
	Minimum		15.00	
	Maximum		23.00	
	Range		8.00	
	Interquartile Range		5.00	
	Skewness		.342	.752
	Kurtosis		-1.533	1.481

Session11	Mean		17.3750	1.11704
	95% Confidence Interval for Mean	Lower Bound	14.7336	
		Upper Bound	20.0164	
	5% Trimmed Mean		17.4167	
	Median		17.5000	
	Variance		9.982	
	Std. Deviation		3.15945	
	Minimum		13.00	
	Maximum		21.00	
	Range		8.00	
	Interquartile Range		6.50	
	Skewness		-.133	.752
	Kurtosis		-1.731	1.481

Extreme Values[a]

			Case Number	Value
Session2	Highest	1	3	23.00
		2	1	21.00
		3	2	21.00
		4	5	19.00
	Lowest	1	7	15.00
		2	8	16.00
		3	4	16.00
		4	6	17.00
Session11	Highest	1	3	21.00
		2	5	21.00
		3	6	20.00
		4	2	18.00
	Lowest	1	4	13.00
		2	8	14.00
		3	7	15.00
		4	1	17.00

a. The requested number of extreme values exceeds the number of data points. A smaller number of extremes is displayed.

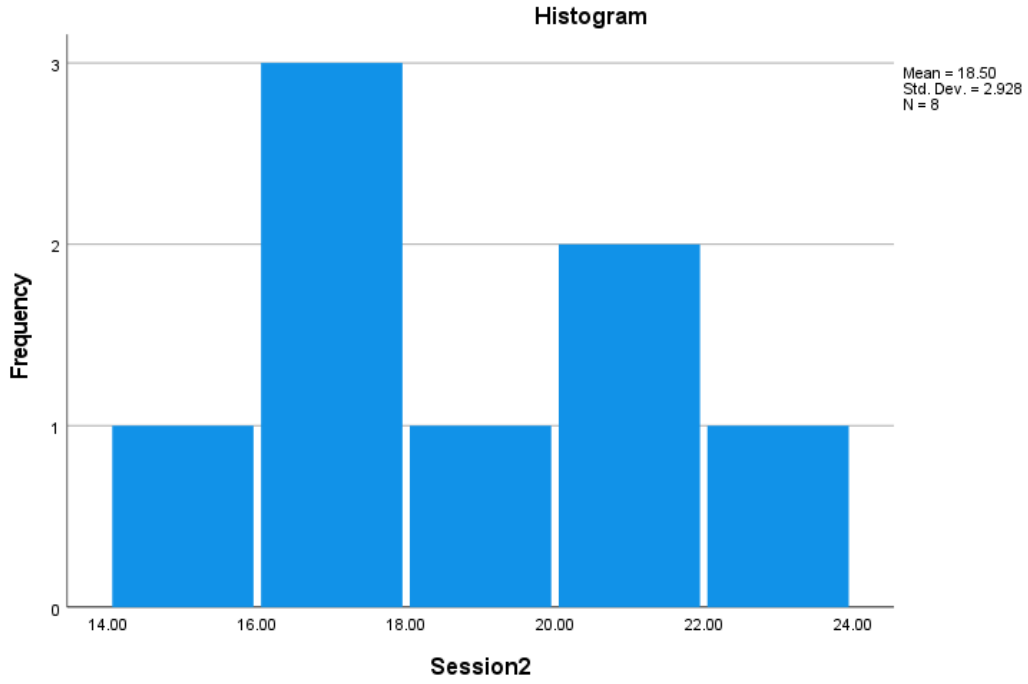
Tests of Normality

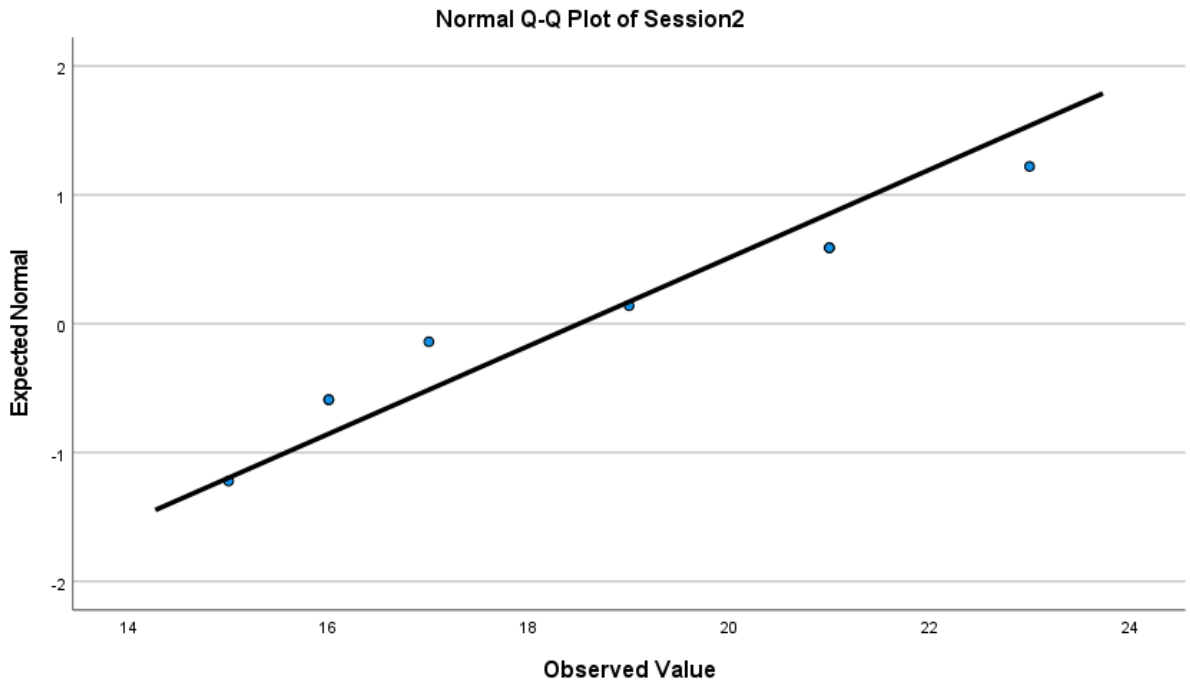
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Session2	.196	8	.200*	.915	8	.393
Session11	.172	8	.200*	.913	8	.375

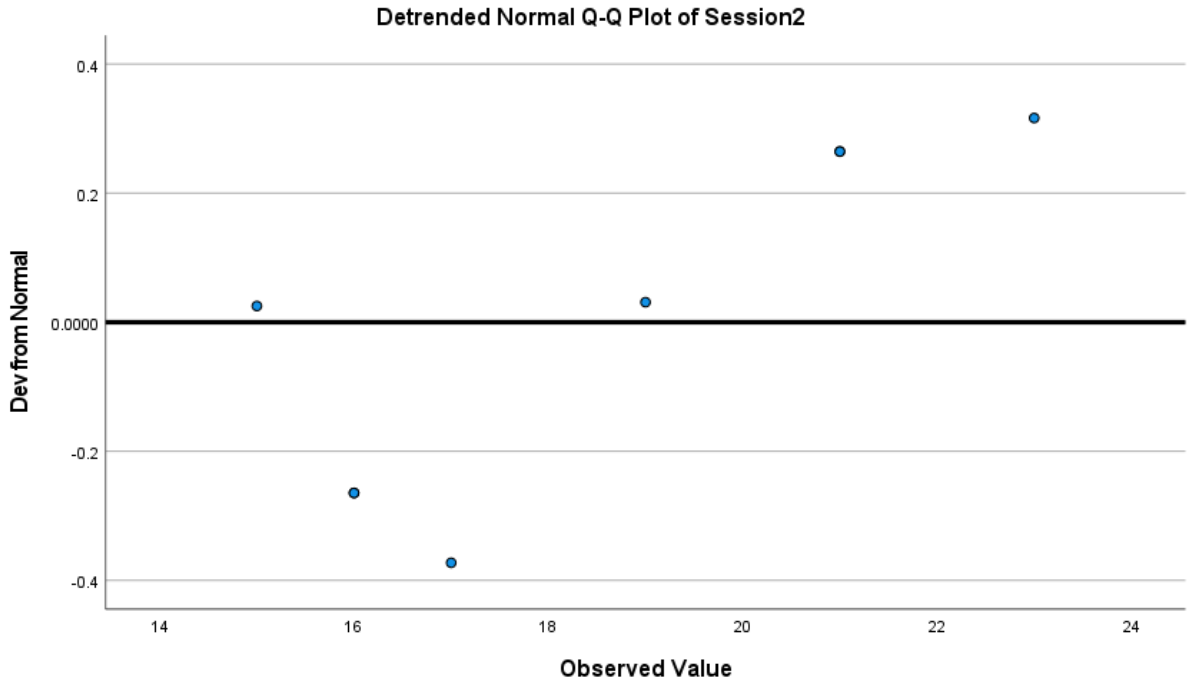
*. This is a lower bound of the true significance.

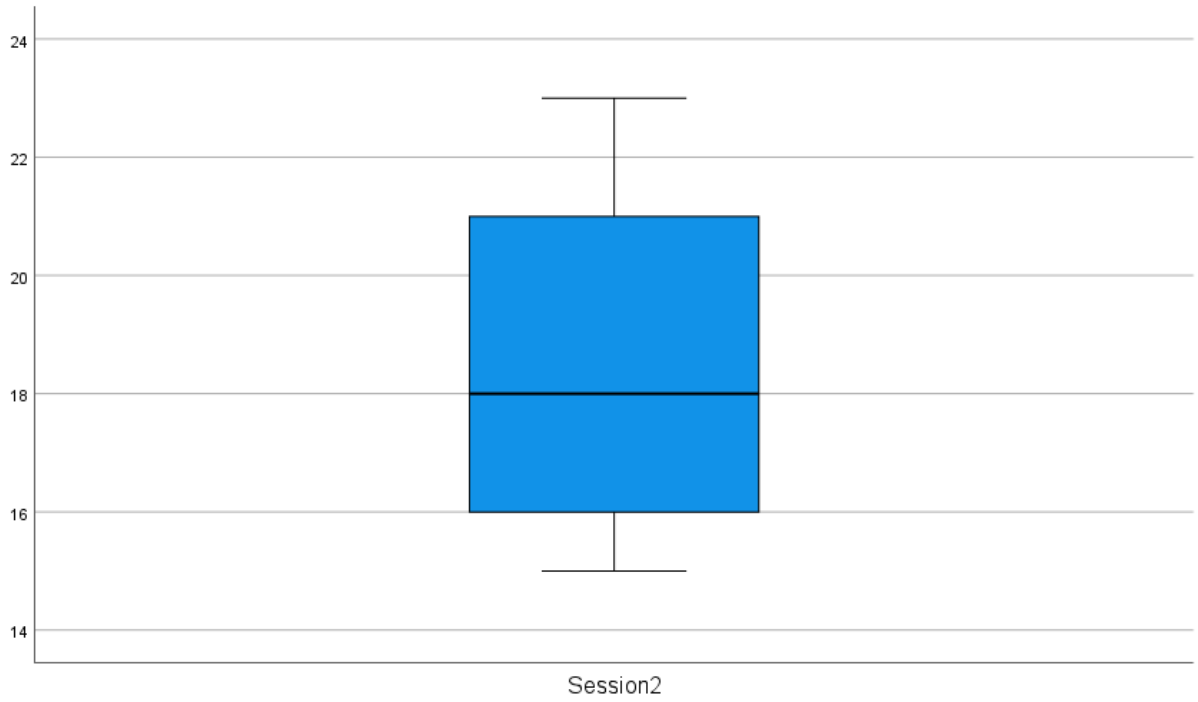
a. Lilliefors Significance Correction

Session2

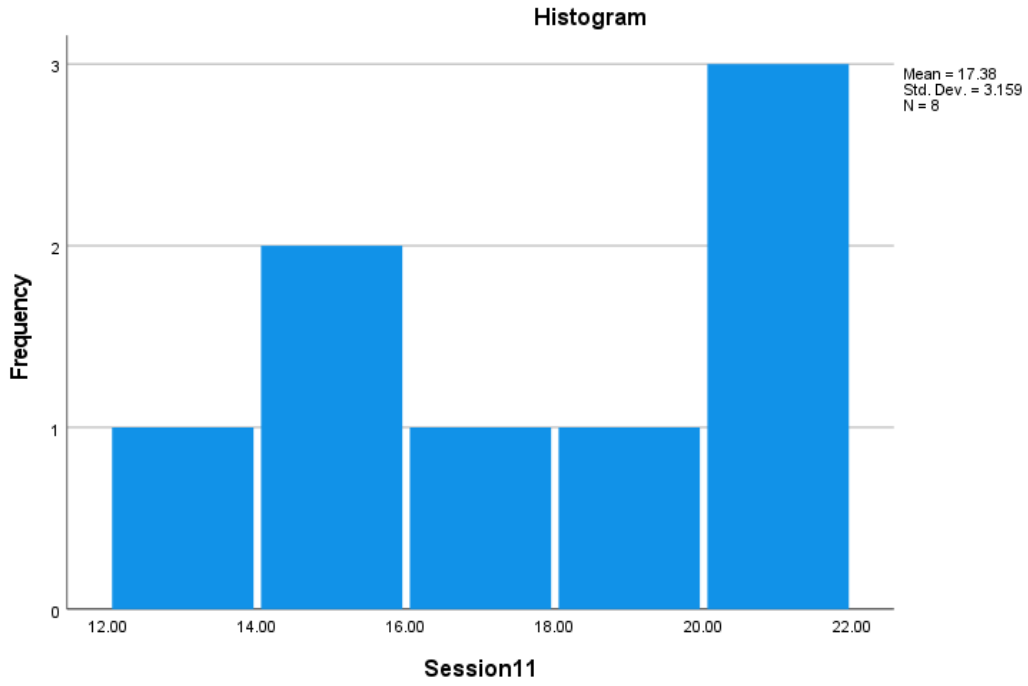


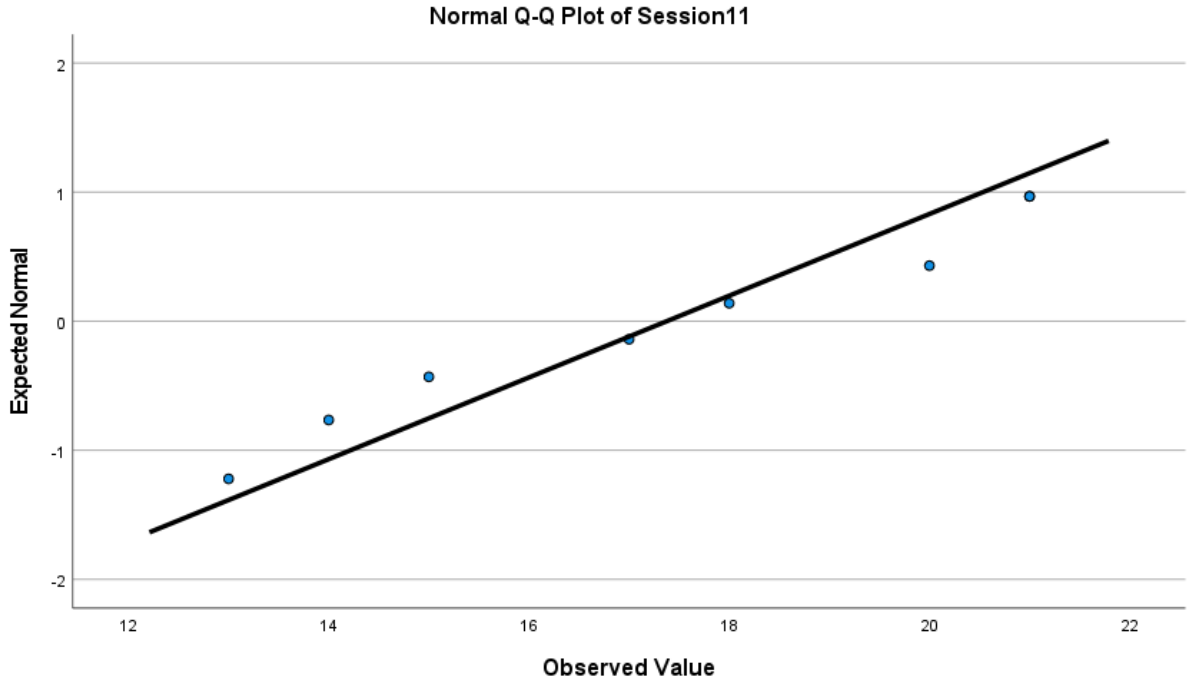

Normal Q-Q Plot of Session2
Expected Normal
2
1
0
-1
-2
14
16
18
20
22
24
Observed Value

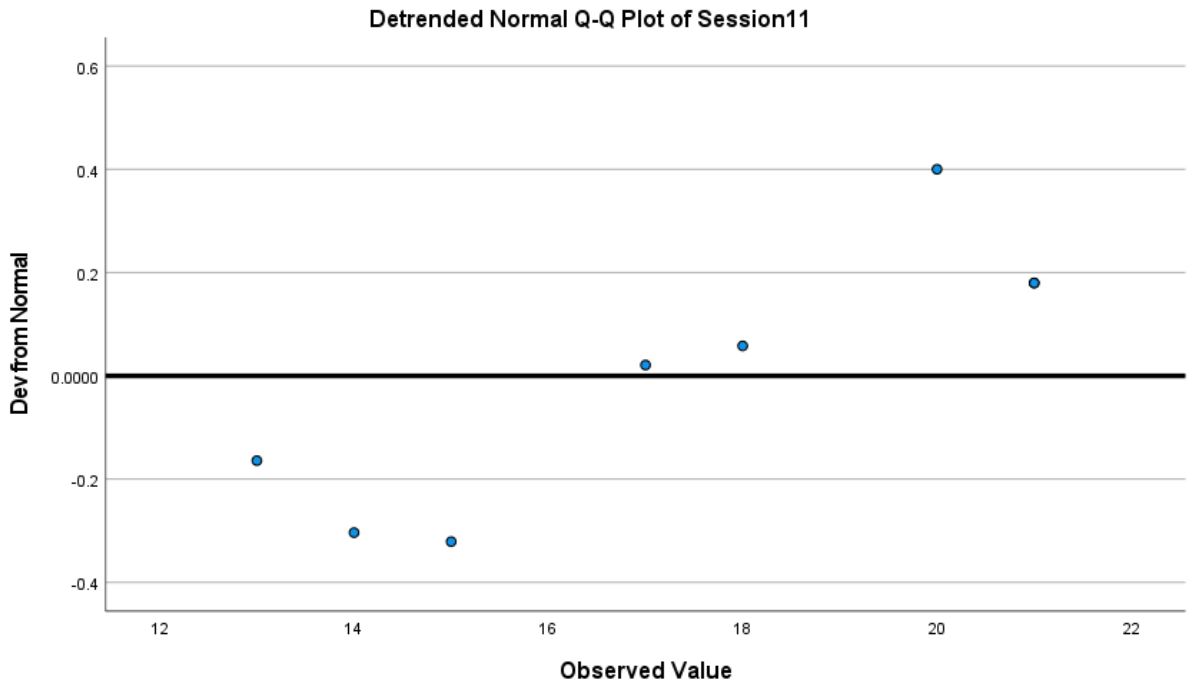

Detrended Normal Q-Q Plot of Session2
Dev from Normal
0.4
0.2
0.0000
-0.2
-0.4
14
16
18
20
22
24
Observed Value

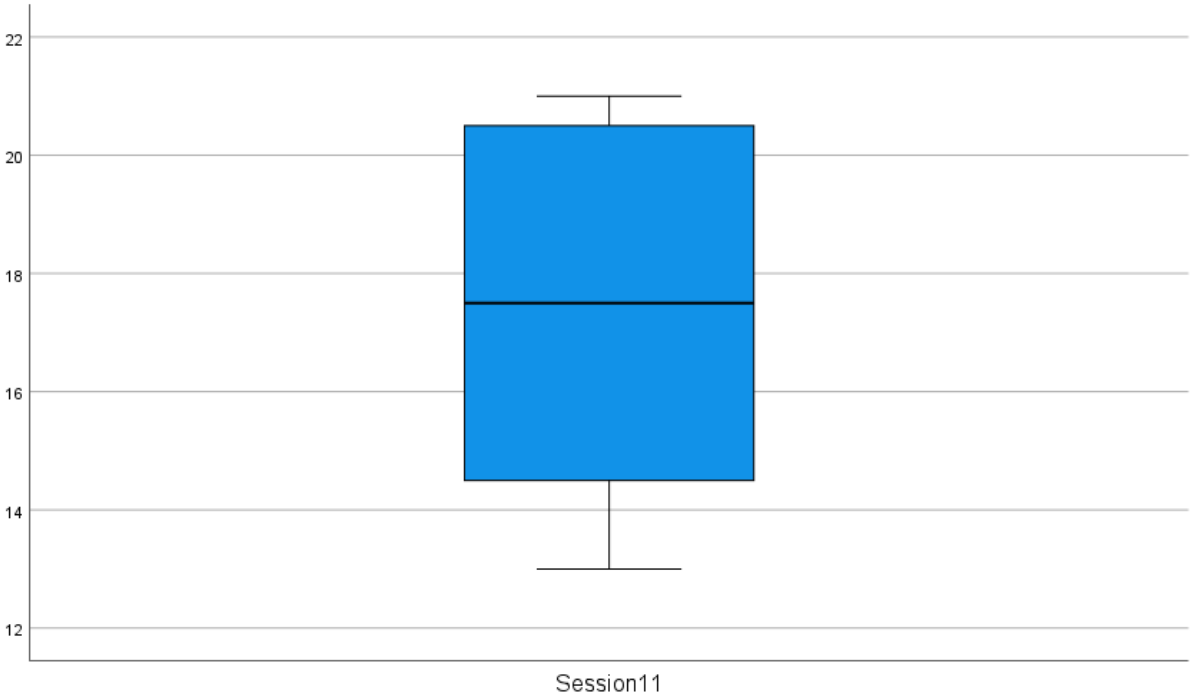


Session11


Histogram
Mean = 17.38
Std. Dev. = 3.159
N = 8
Frequency
3
2
1
0
12.00
14.00
16.00
18.00
20.00
22.00
Session11


Normal Q-Q Plot of Session11
Expected Normal
2
1
0
-1
-2
12
14
16
18
20
22
Observed Value


Detrended Normal Q-Q Plot of Session11
Dev from Normal
0.6
0.4
0.2
0.0000
-0.2
-0.4
12
14
16
18
20
22
Observed Value


22
20
18
16
14
12
Session11

```
NPAR TESTS
  /M-W= FCRS1 BY group(1 2)
```

NPar Tests

Notes

Output Created		18-JUL-2020 17:21:57
Comments		
Input	Active Dataset	DataSet2
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	16
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics for each test are based on all cases with valid data for the variable(s) used in that test.
Syntax		NPAR TESTS /M-W= FCRS1 BY group(1 2) /MISSING ANALYSIS.
Resources	Processor Time	00:00:00.02
	Elapsed Time	00:00:00.01
	Number of Cases Allowed[a]	449389

a. Based on availability of workspace memory.

Mann-Whitney Test

Ranks

	group	N	Mean Rank	Sum of Ranks
FCRS1	1.00	8	9.38	75.00
	2.00	8	7.63	61.00
	Total	16		

Test Statistics[a]

	FCRS1
Mann-Whitney U	25.000
Wilcoxon W	61.000
Z	-.742
Asymp. Sig. (2-tailed)	.458
Exact Sig. [2*(1-tailed Sig.)]	.505[b]

a. Grouping Variable: group

b. Not corrected for ties.

```
FCRS3
NEW FILE.
DATASET NAME DataSet1 WINDOW=FRONT.
DATASET ACTIVATE DataSet1.
DATASET CLOSE DataSet0.
EXAMINE VARIABLES=Session2 Session10
  /PLOT BOXPLOT HISTOGRAM NPPLOT
  /COMPARE GROUPS
  /STATISTICS DESCRIPTIVES EXTREME
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.
```

Explore

Notes

Output Created		18-JUL-2020 11:18:19
Comments		
Input	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	8
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.

Syntax		EXAMINE VARIABLES=Session2 Session10 /PLOT BOXPLOT HISTOGRAM NPPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE /NOTOTAL.
Resources	Processor Time	00:00:01.92
	Elapsed Time	00:00:01.27

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Session2	8	100.0%	0	0.0%	8	100.0%
Session10	8	100.0%	0	0.0%	8	100.0%

Descriptives

			Statistic	Std. Error
Session2	Mean		14.3750	1.51112
	95% Confidence Interval for Mean	Lower Bound	10.8018	
		Upper Bound	17.9482	
	5% Trimmed Mean		14.2500	
	Median		14.0000	
	Variance		18.268	
	Std. Deviation		4.27409	
	Minimum		9.00	
	Maximum		22.00	
	Range		13.00	
	Interquartile Range		7.00	
	Skewness		.592	.752
	Kurtosis		.024	1.481

Session10	Mean		20.7500	1.19149
	95% Confidence Interval for Mean	Lower Bound	17.9326	
		Upper Bound	23.5674	
	5% Trimmed Mean		20.8889	
	Median		22.0000	
	Variance		11.357	
	Std. Deviation		3.37004	
	Minimum		15.00	
	Maximum		24.00	
	Range		9.00	
	Interquartile Range		5.75	
	Skewness		-1.176	.752
	Kurtosis		-.195	1.481

Extreme Values[a]

			Case Number	Value
Session2	Highest	1	8	22.00
		2	7	18.00
		3	2	16.00
		4	1	14.00[b]
	Lowest	1	4	9.00
		2	5	10.00
		3	3	12.00
		4	6	14.00[c]
Session10	Highest	1	1	24.00
		2	6	23.00
		3	8	23.00
		4	3	22.00[d]
	Lowest	1	5	15.00
		2	7	16.00
		3	2	21.00
		4	4	22.00[e]

a. The requested number of extreme values exceeds the number of data points. A smaller number of extremes is displayed.

b. Only a partial list of cases with the value 14.00 are shown in the table of upper extremes.

c. Only a partial list of cases with the value 14.00 are shown in the table of lower extremes.

d. Only a partial list of cases with the value 22.00 are shown in the table of upper extremes.

e. Only a partial list of cases with the value 22.00 are shown in the table of lower extremes.

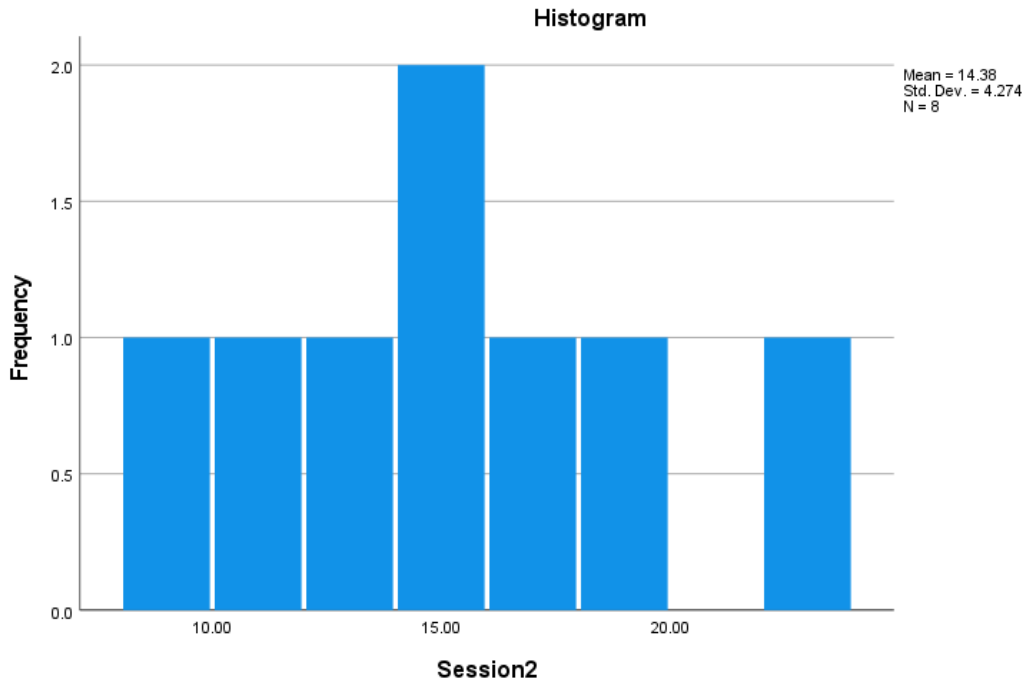
Tests of Normality

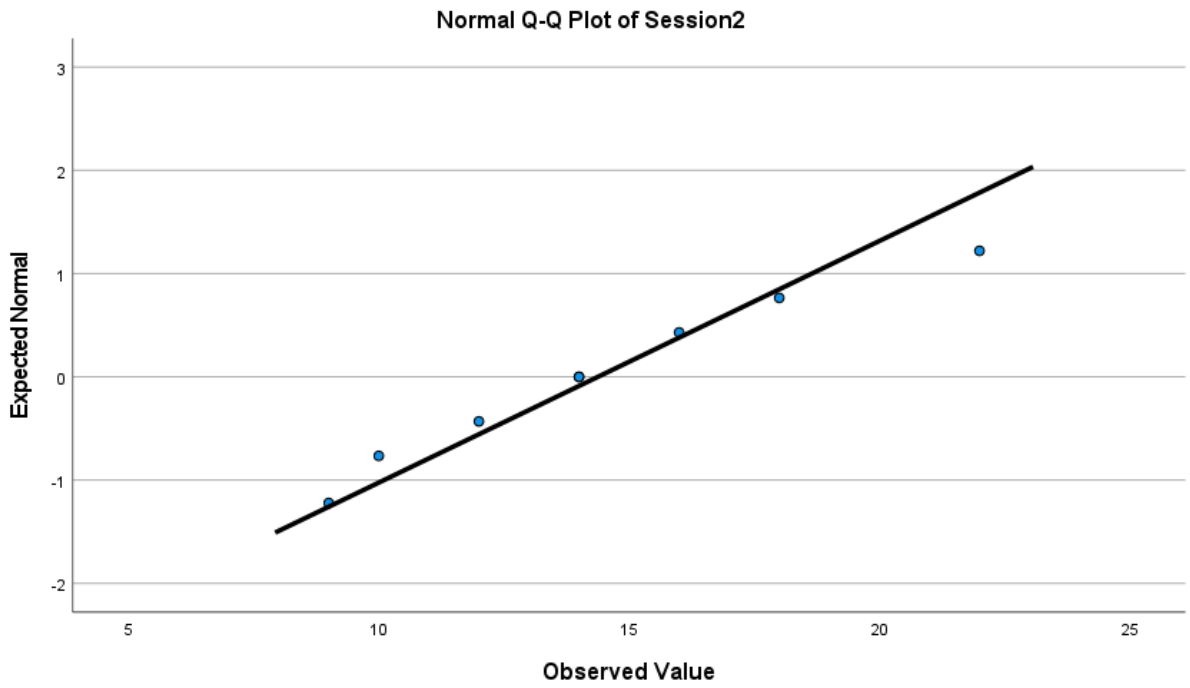
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Session2	.160	8	.200*	.963	8	.838
Session10	.280	8	.065	.807	8	.034

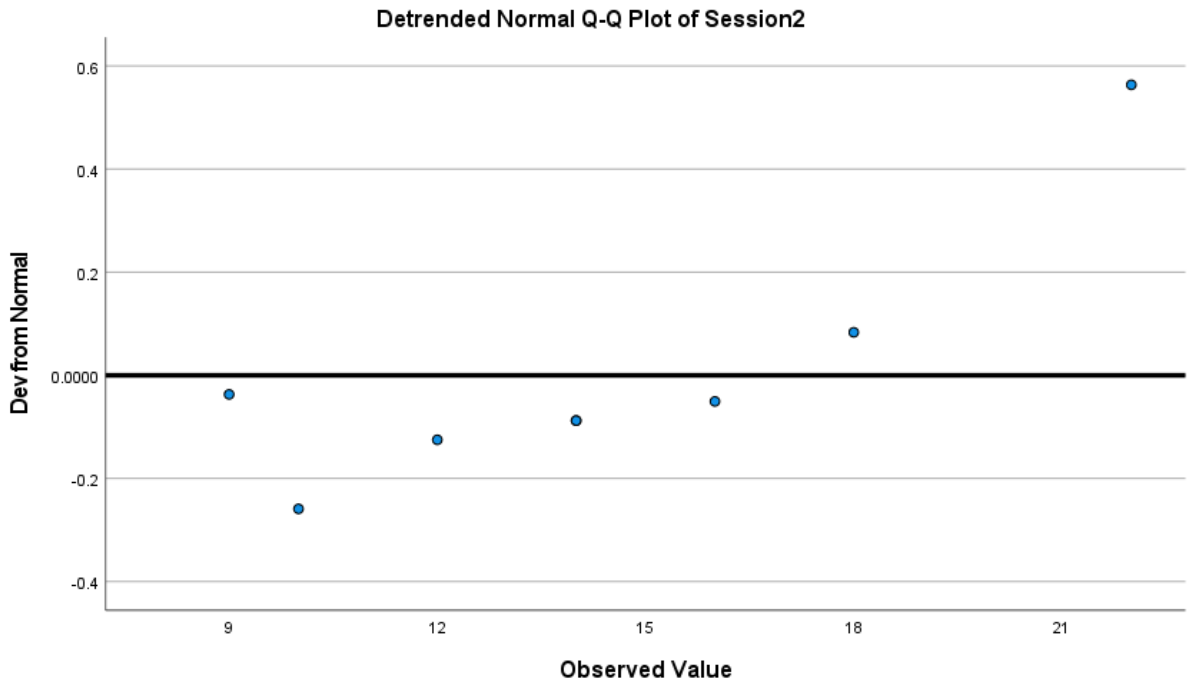
*. This is a lower bound of the true significance.

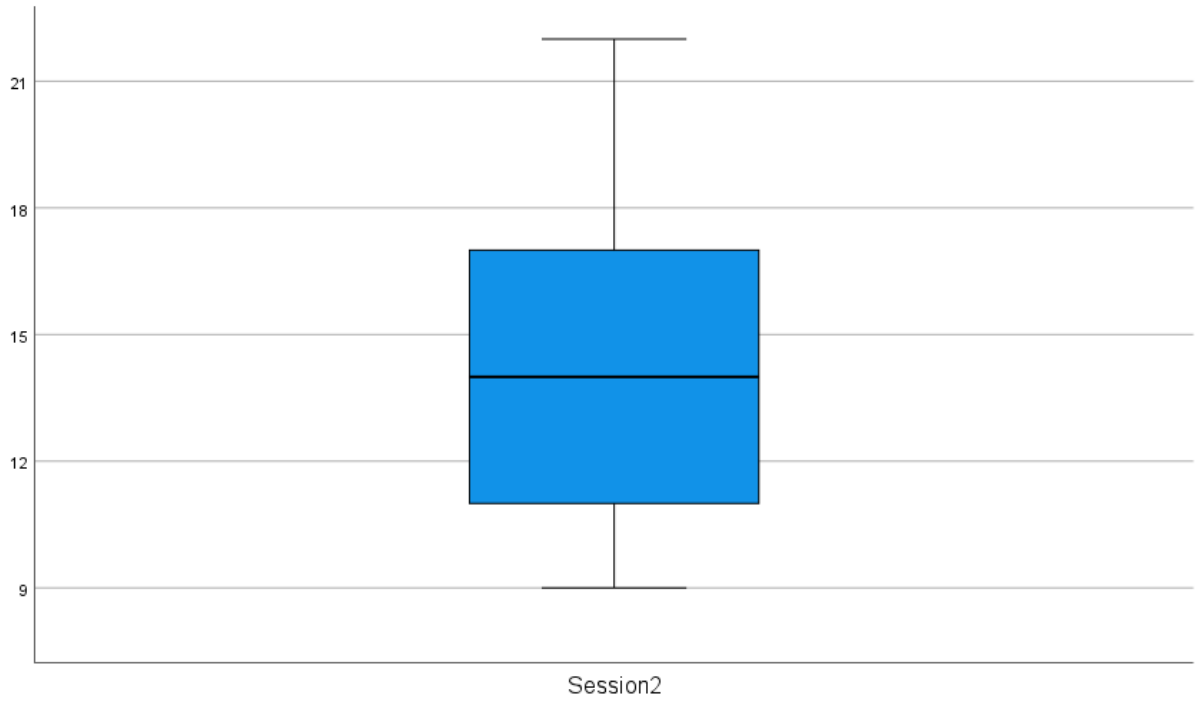
a. Lilliefors Significance Correction

Session2

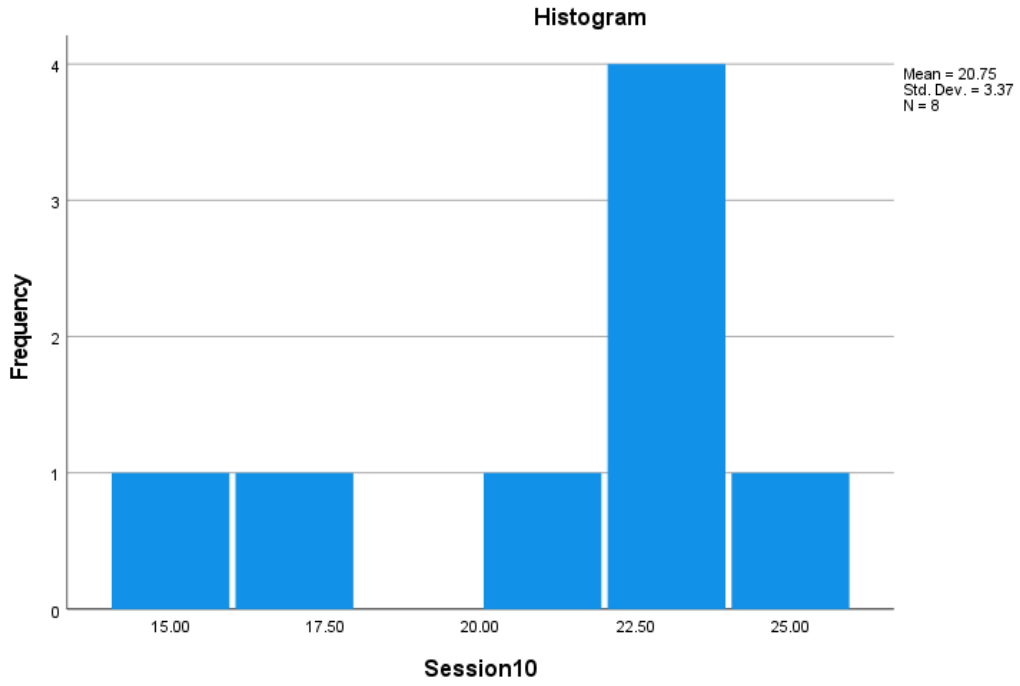


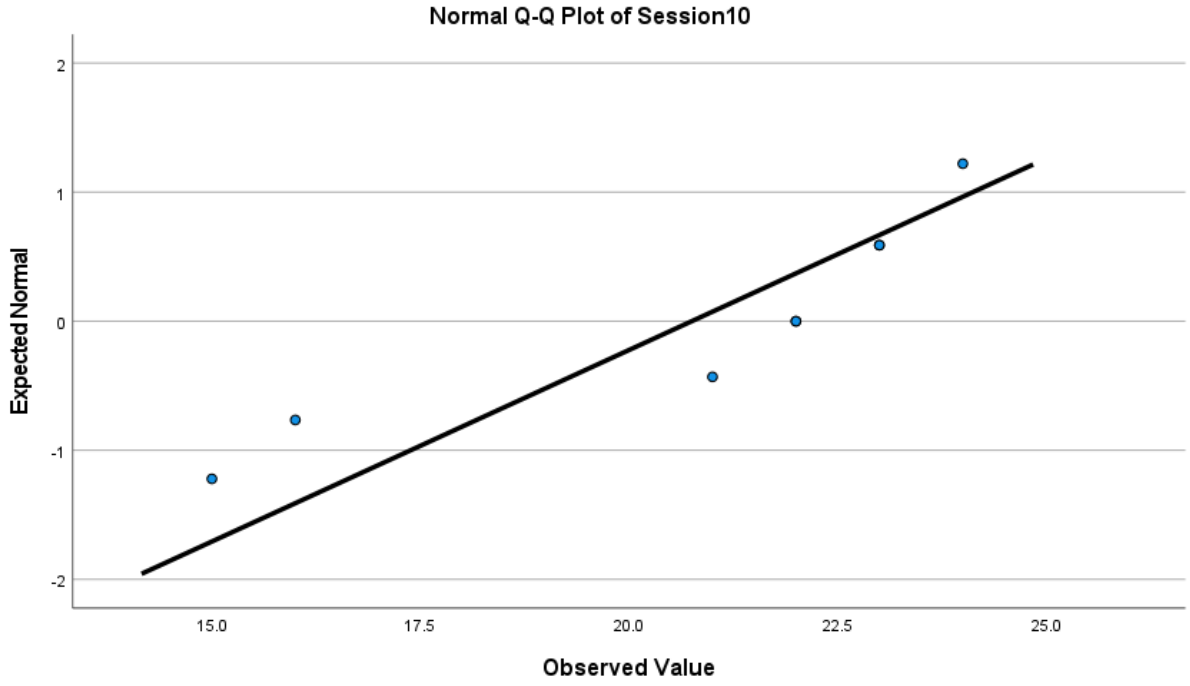

Normal Q-Q Plot of Session2
Expected Normal
3
2
1
0
-1
-2
5
10
15
20
25
Observed Value

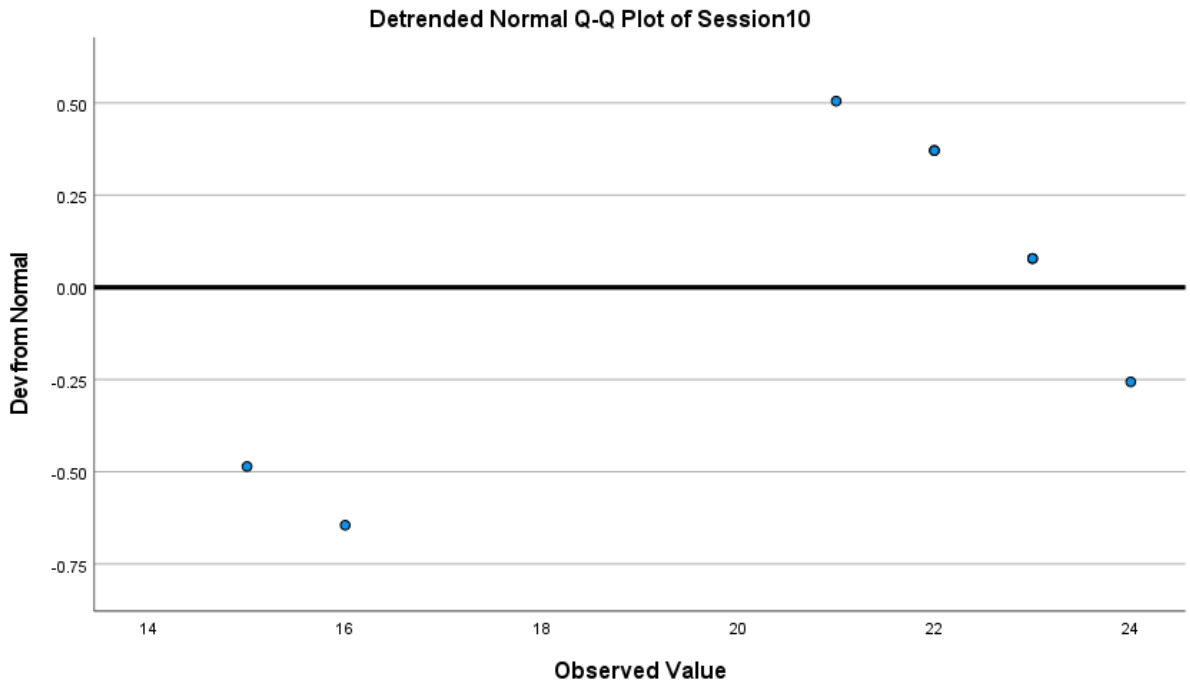

Detrended Normal Q-Q Plot of Session2
Dev from Normal
0.6
0.4
0.2
0.0000
-0.2
-0.4
9
12
15
18
21
Observed Value

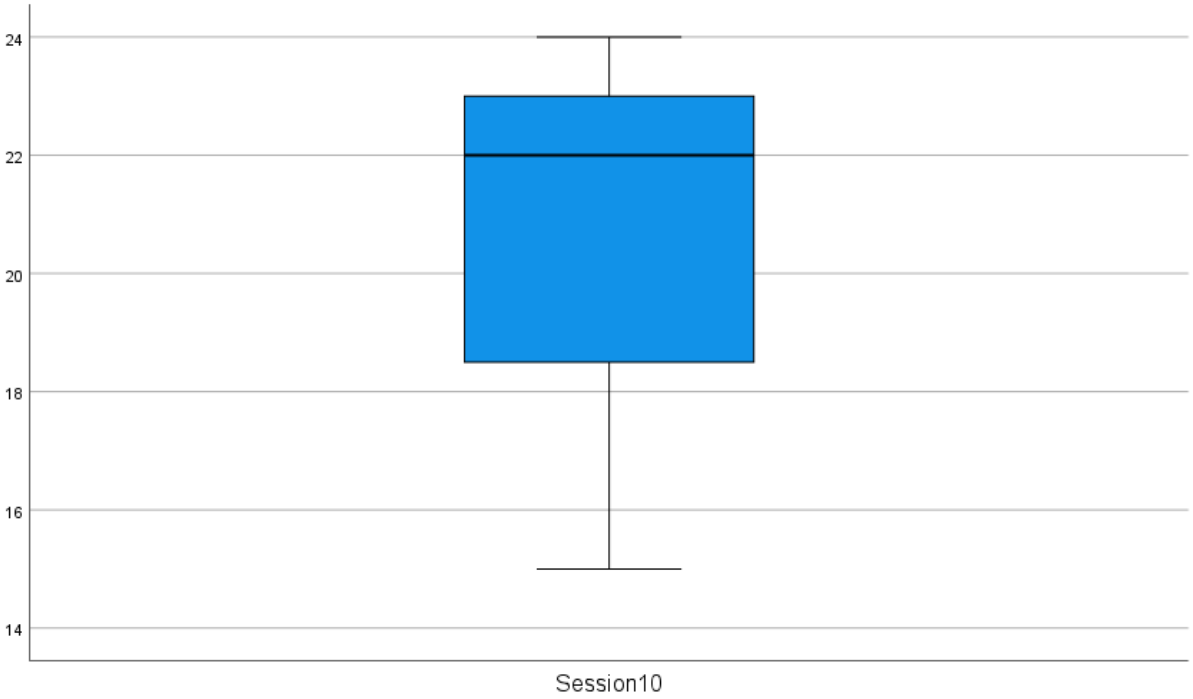


Session10


Histogram
Mean = 20.75
Std. Dev. = 3.37
N = 8
Frequency
4
3
2
1
0
15.00
17.50
20.00
22.50
25.00
Session10


Normal Q-Q Plot of Session10
Expected Normal
2
1
0
-1
-2
15.0
17.5
20.0
22.5
25.0
Observed Value


Detrended Normal Q-Q Plot of Session10
Dev from Normal
0.50
0.25
0.00
-0.25
-0.50
-0.75
14
16
18
20
22
24
Observed Value


24
22
20
18
16
14
Session10

```
NPAR TESTS
  /M-W= FCRS3 BY group(1 2)
```

NPar Tests

Notes

Output Created		18-JUL-2020 17:21:04
Comments		
Input	Active Dataset	DataSet2
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	16
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics for each test are based on all cases with valid data for the variable(s) used in that test.
Syntax		NPAR TESTS /M-W= FCRS3 BY group(1 2) /MISSING ANALYSIS.
Resources	Processor Time	00:00:00.00
	Elapsed Time	00:00:00.01
	Number of Cases Allowed[a]	449389

a. Based on availability of workspace memory.

Mann-Whitney Test

Ranks

	group	N	Mean Rank	Sum of Ranks
FCRS3	1.00	8	5.44	43.50
	2.00	8	11.56	92.50
	Total	16		

Test Statistics[a]

	FCRS3
Mann-Whitney U	7.500
Wilcoxon W	43.500
Z	-2.586
Asymp. Sig. (2-tailed)	.010
Exact Sig. [2*(1-tailed Sig.)]	.007[b]

a. Grouping Variable: group

b. Not corrected for ties.

```
FCRS5
EXAMINE VARIABLES=Session2 Session14
  /PLOT BOXPLOT HISTOGRAM NPPLOT
  /COMPARE GROUPS
  /STATISTICS DESCRIPTIVES EXTREME
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.
```

Explore

Notes

Output Created		18-JUL-2020 11:26:31
Comments		
Input	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	8
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.

Syntax		EXAMINE VARIABLES=Session2 Session14 /PLOT BOXPLOT HISTOGRAM NPPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE /NOTOTAL.
Resources	Processor Time	00:00:01.31
	Elapsed Time	00:00:01.18

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Session2	8	100.0%	0	0.0%	8	100.0%
Session14	8	100.0%	0	0.0%	8	100.0%

Descriptives

			Statistic	Std. Error
Session2	Mean		23.8750	1.30161
	95% Confidence Interval for Mean	Lower Bound	20.7972	
		Upper Bound	26.9528	
	5% Trimmed Mean		23.9167	
	Median		23.5000	
	Variance		13.554	
	Std. Deviation		3.68152	
	Minimum		18.00	
	Maximum		29.00	
	Range		11.00	
	Interquartile Range		6.25	
	Skewness		-.074	.752
	Kurtosis		-.659	1.481

Session14	Mean		24.3750	.70553
	95% Confidence Interval for Mean	Lower Bound	22.7067	
		Upper Bound	26.0433	
	5% Trimmed Mean		24.3056	
	Median		24.0000	
	Variance		3.982	
	Std. Deviation		1.99553	
	Minimum		22.00	
	Maximum		28.00	
	Range		6.00	
	Interquartile Range		2.75	
	Skewness		.748	.752
	Kurtosis		-.089	1.481

Extreme Values[a]

			Case Number	Value
Session2	Highest	1	3	29.00
		2	7	28.00
		3	2	26.00
		4	8	24.00
	Lowest	1	1	18.00
		2	6	21.00
		3	5	22.00
		4	4	23.00
Session14	Highest	1	2	28.00
		2	1	26.00
		3	3	25.00
		4	7	25.00
	Lowest	1	8	22.00
		2	6	23.00
		3	5	23.00
		4	4	23.00

a. The requested number of extreme values exceeds the number of data points. A smaller number of extremes is displayed.

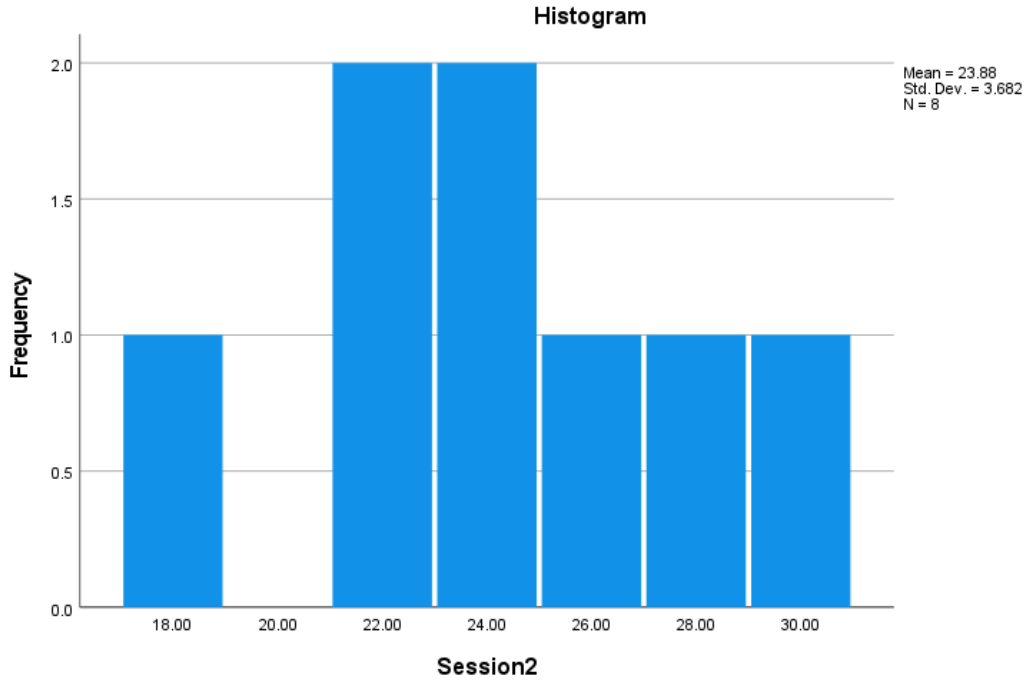
Tests of Normality

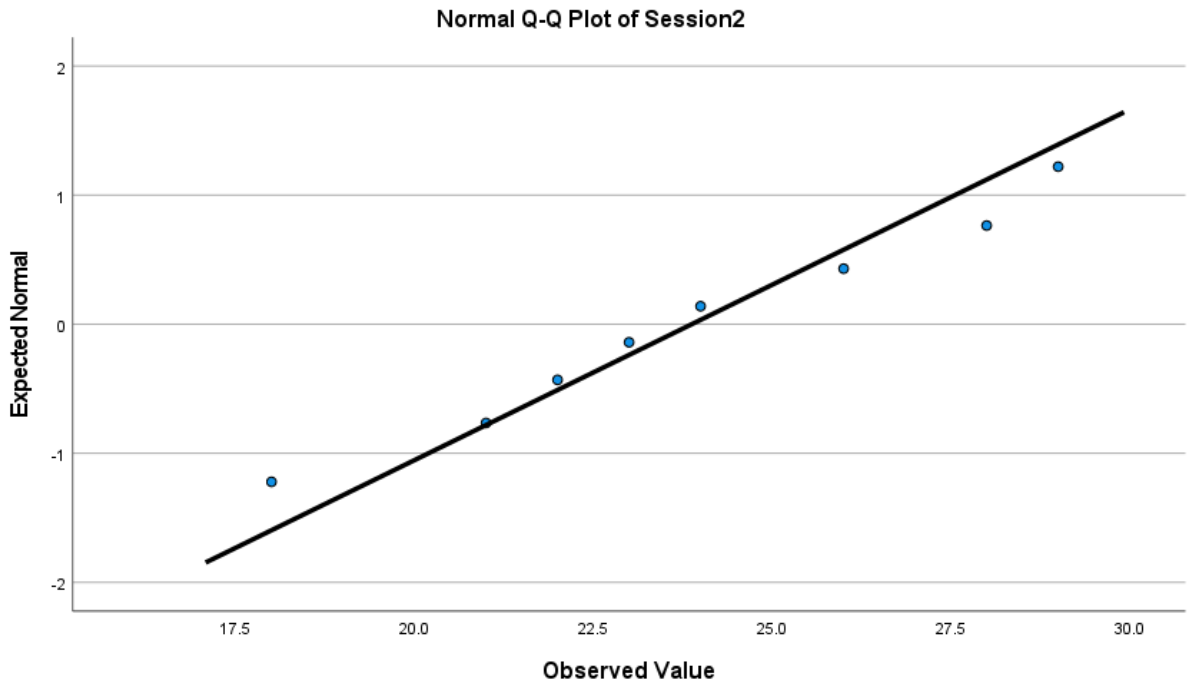
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Session2	.119	8	.200*	.977	8	.945
Session14	.255	8	.136	.912	8	.370

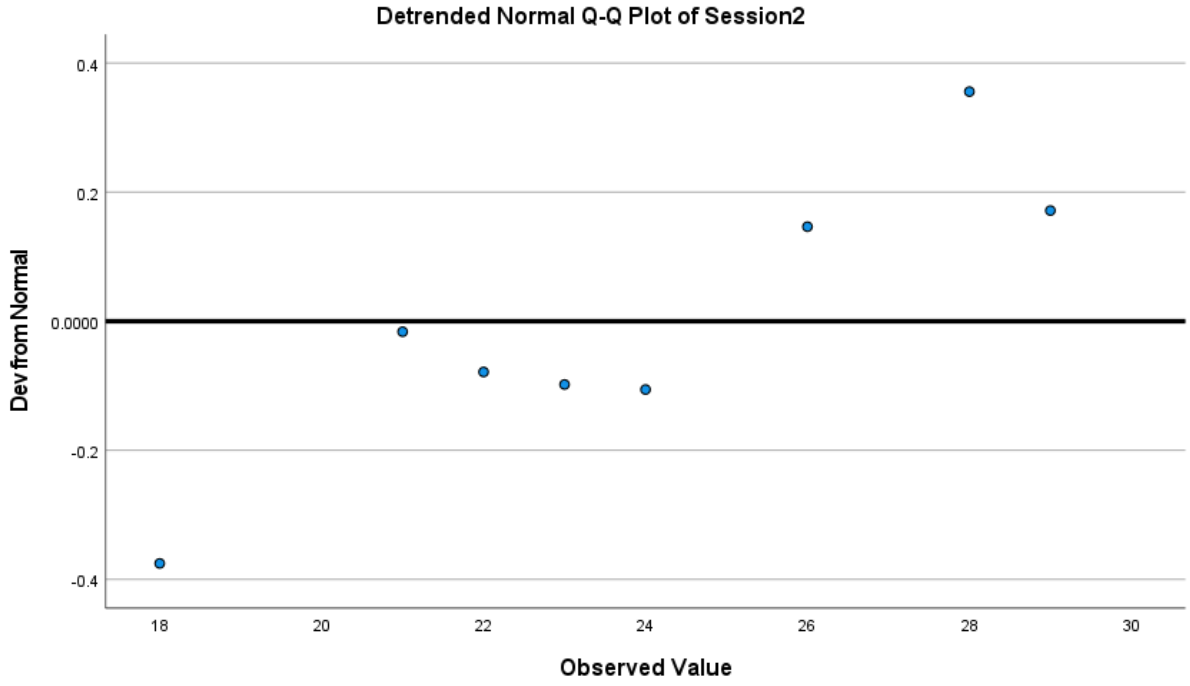
*. This is a lower bound of the true significance.

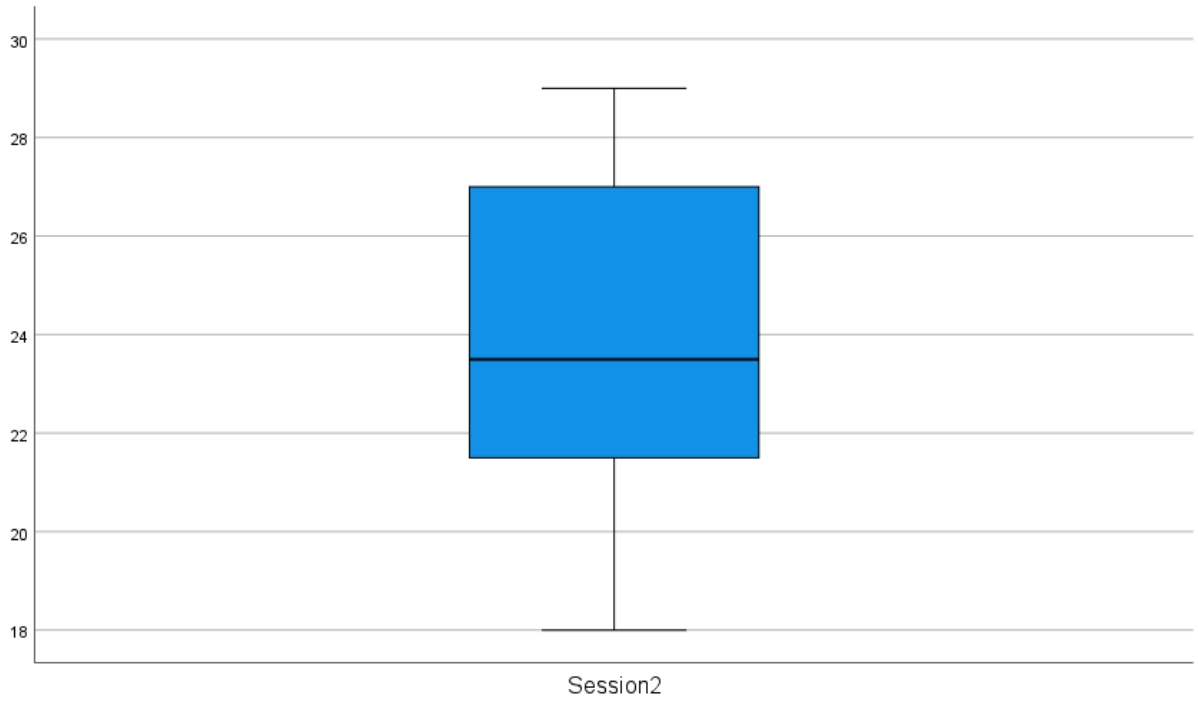
a. Lilliefors Significance Correction

Session2

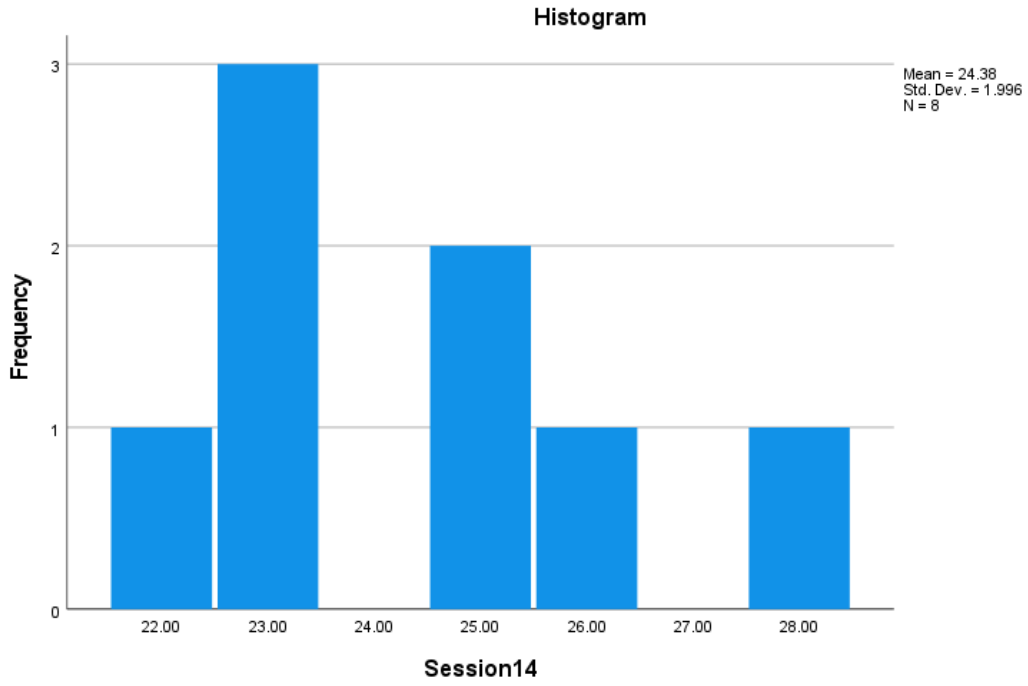


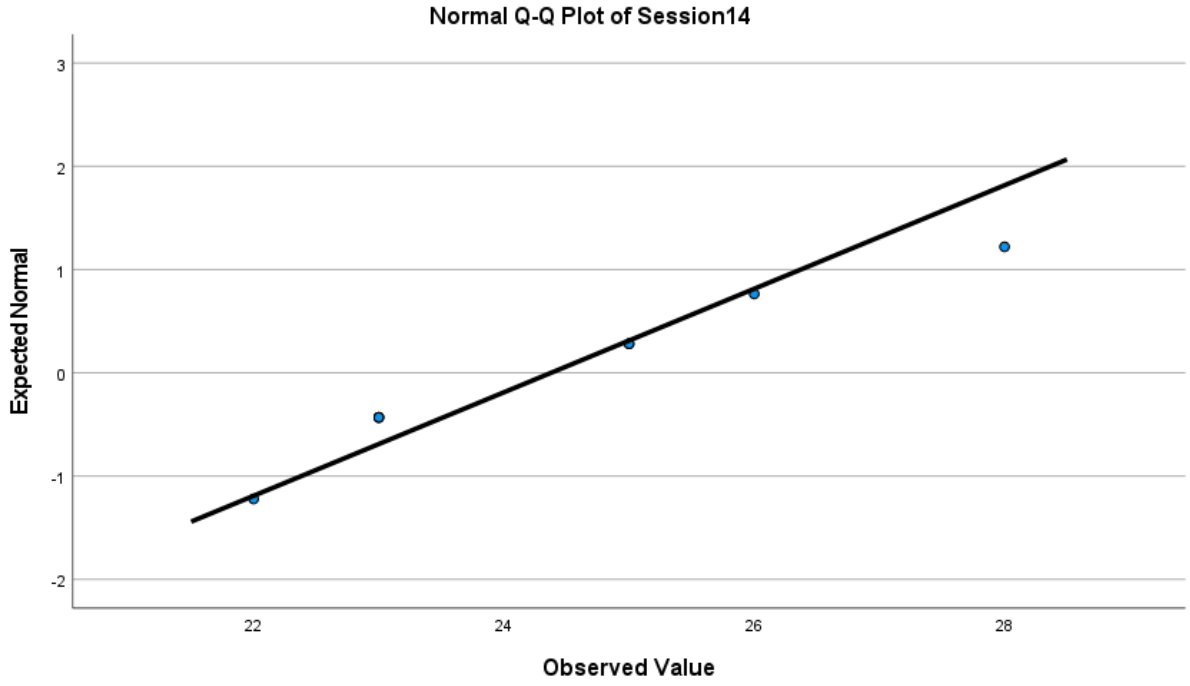

Normal Q-Q Plot of Session2
Expected Normal
2
1
0
-1
-2
17.5
20.0
22.5
25.0
27.5
30.0
Observed Value

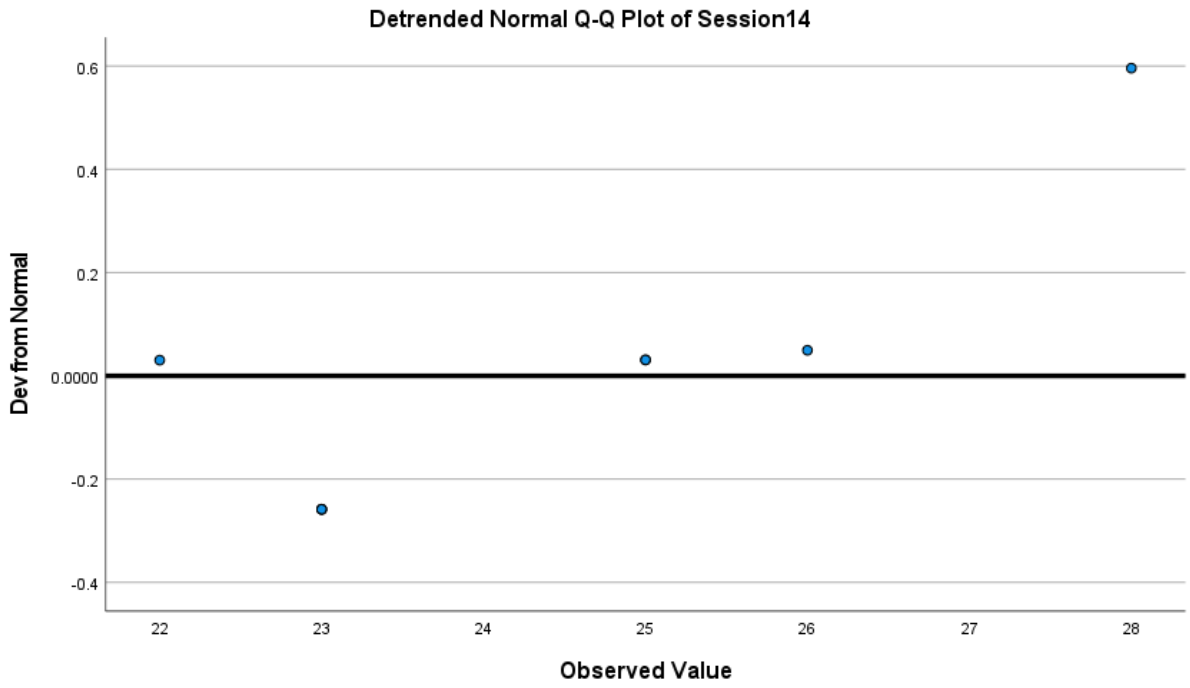

Detrended Normal Q-Q Plot of Session2
Dev from Normal
0.4
0.2
0.0000
-0.2
-0.4
18
20
22
24
26
28
30
Observed Value

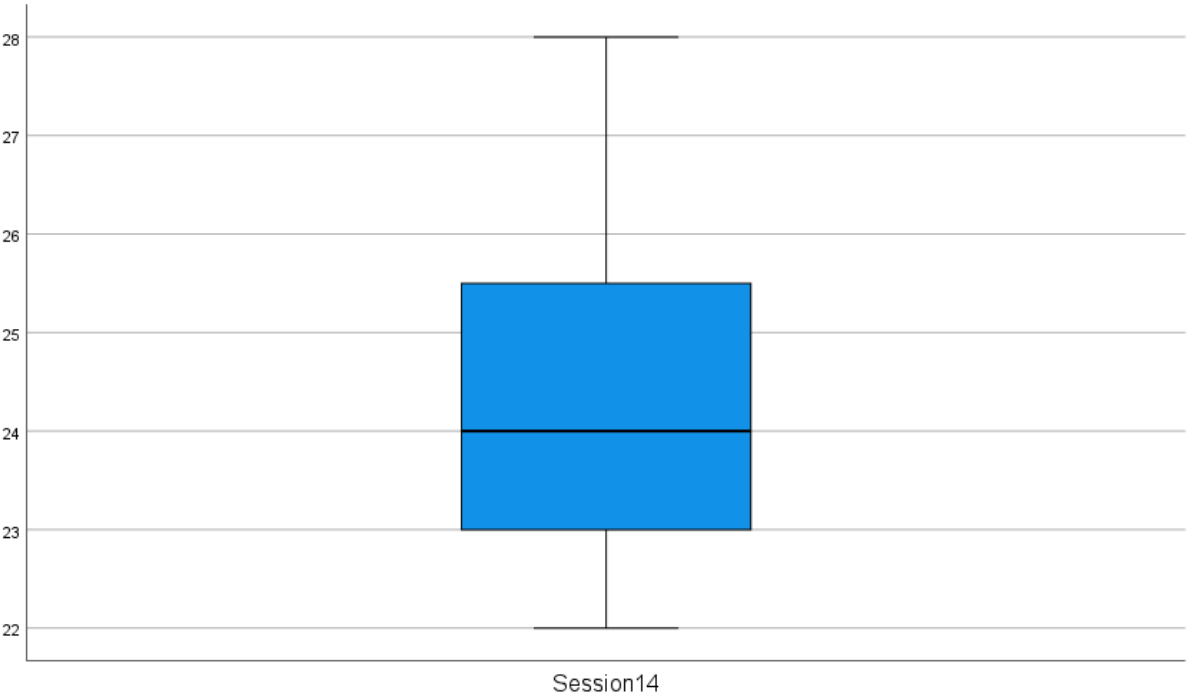


Session14


Histogram
Mean = 24.38
Std. Dev. = 1.996
N = 8
Frequency
3
2
1
0
22.00
23.00
24.00
25.00
26.00
27.00
28.00
Session14


Normal Q-Q Plot of Session14
Expected Normal
3
2
1
0
-1
-2
22
24
26
28
Observed Value


Detrended Normal Q-Q Plot of Session14
Dev from Normal
0.6
0.4
0.2
0.0000
-0.2
-0.4
22
23
24
25
26
27
28
Observed Value


28
27
26
25
24
23
22
Session14

```
NPAR TESTS
  /M-W= FCRS5 BY group(1 2)
```

NPar Tests

Notes

Output Created		18-JUL-2020 17:20:03
Comments		
Input	Active Dataset	DataSet2
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	16
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics for each test are based on all cases with valid data for the variable(s) used in that test.
Syntax		NPAR TESTS /M-W= FCRS5 BY group(1 2) /MISSING ANALYSIS.
Resources	Processor Time	00:00:00.02
	Elapsed Time	00:00:00.01
	Number of Cases Allowed[a]	449389

a. Based on availability of workspace memory.

Mann-Whitney Test

Ranks

	group	N	Mean Rank	Sum of Ranks
FCRS5	1.00	8	8.13	65.00
	2.00	8	8.88	71.00
	Total	16		

Test Statistics[a]

	FCRS5
Mann-Whitney U	29.000
Wilcoxon W	65.000
Z	-.318
Asymp. Sig. (2-tailed)	.750
Exact Sig. [2*(1-tailed Sig.)]	.798[b]

a. Grouping Variable: group

b. Not corrected for ties.

```
FCRS8
EXAMINE VARIABLES=Session2 Session10
  /PLOT BOXPLOT HISTOGRAM NPPLOT
  /COMPARE GROUPS
  /STATISTICS DESCRIPTIVES EXTREME
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.
```

Explore

Notes

Output Created		18-JUL-2020 11:28:49
Comments		
Input	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	8
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.

Syntax		EXAMINE VARIABLES=Session2 Session10 /PLOT BOXPLOT HISTOGRAM NPPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE /NOTOTAL.
Resources	Processor Time	00:00:01.17
	Elapsed Time	00:00:01.14

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Session2	8	100.0%	0	0.0%	8	100.0%
Session10	8	100.0%	0	0.0%	8	100.0%

Descriptives

			Statistic	Std. Error
Session2	Mean		19.7500	1.14564
	95% Confidence Interval for Mean	Lower Bound	17.0410	
		Upper Bound	22.4590	
	5% Trimmed Mean		19.8333	
	Median		20.0000	
	Variance		10.500	
	Std. Deviation		3.24037	
	Minimum		15.00	
	Maximum		23.00	
	Range		8.00	
	Interquartile Range		6.50	
	Skewness		-.340	.752
	Kurtosis		-1.623	1.481

Session10	Mean		25.5000	.46291
	95% Confidence Interval for Mean	Lower Bound	24.4054	
		Upper Bound	26.5946	
	5% Trimmed Mean		25.5000	
	Median		26.0000	
	Variance		1.714	
	Std. Deviation		1.30931	
	Minimum		24.00	
	Maximum		27.00	
	Range		3.00	
	Interquartile Range		2.75	
	Skewness		-.255	.752
	Kurtosis		-1.925	1.481

Extreme Values[a]

			Case Number	Value
Session2	Highest	1	2	23.00
		2	4	23.00
		3	6	23.00
		4	7	21.00
	Lowest	1	3	15.00
		2	8	16.00
		3	5	18.00
		4	1	19.00
Session10	Highest	1	1	27.00
		2	5	27.00
		3	2	26.00
		4	4	26.00[b]
	Lowest	1	8	24.00
		2	6	24.00
		3	3	24.00
		4	7	26.00[c]

a. The requested number of extreme values exceeds the number of data points. A smaller number of extremes is displayed.

b. Only a partial list of cases with the value 26.00 are shown in the table of upper extremes.

c. Only a partial list of cases with the value 26.00 are shown in the table of lower extremes.

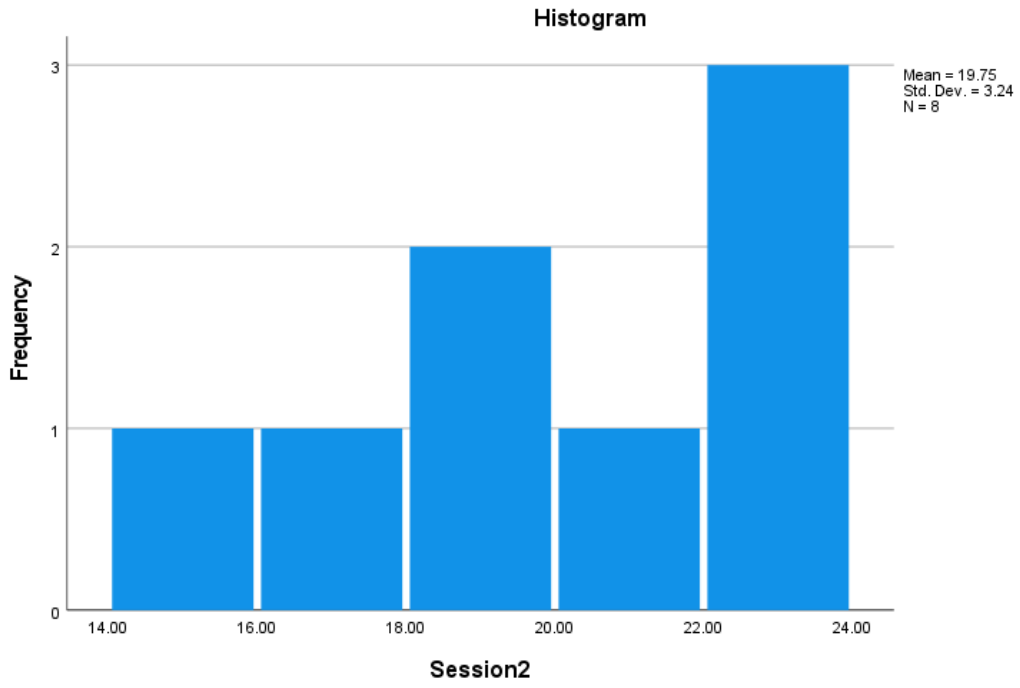
Tests of Normality

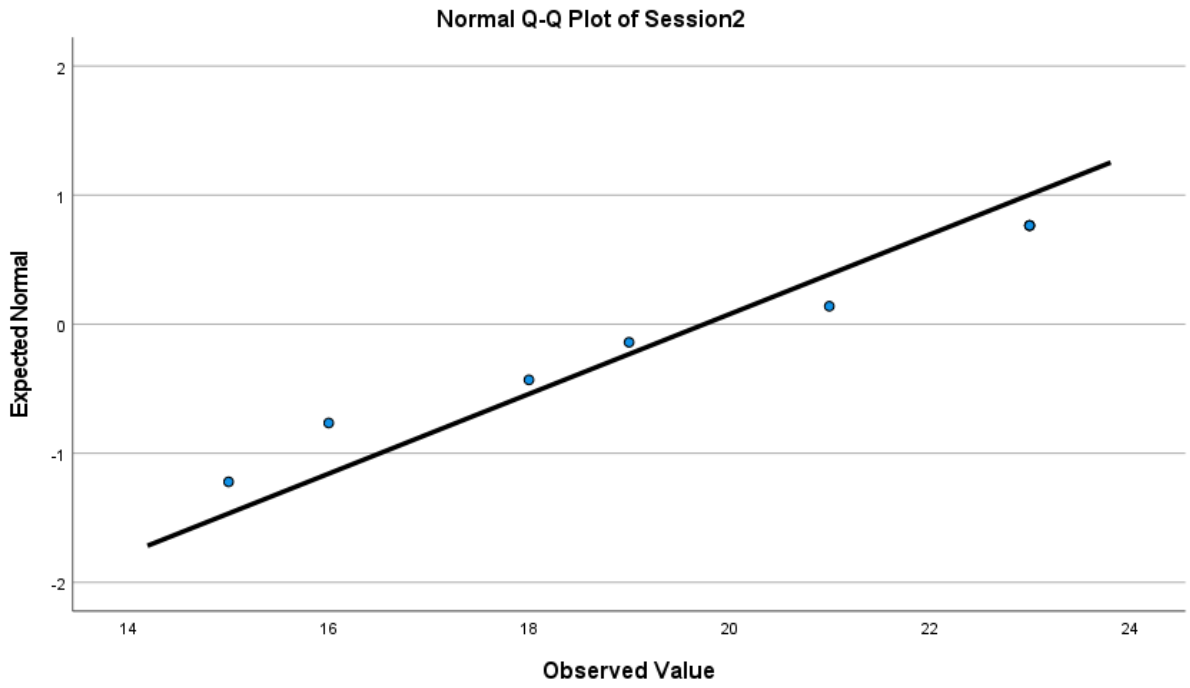
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Session2	.217	8	.200*	.880	8	.189
Session10	.274	8	.079	.808	8	.035

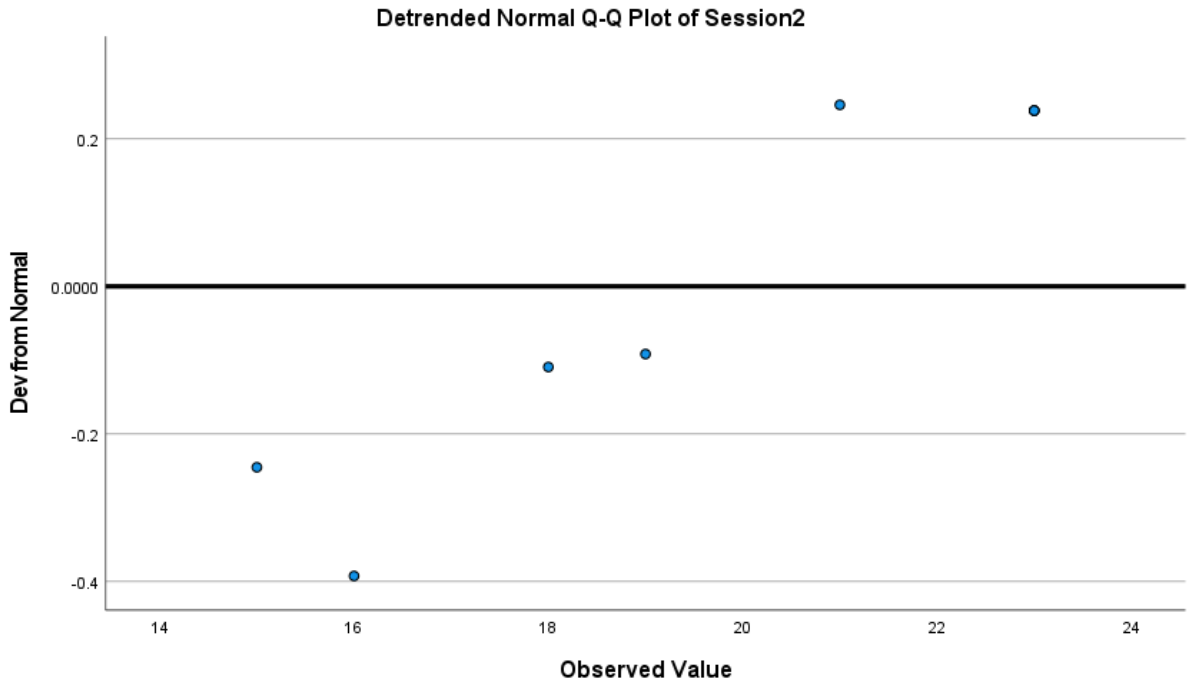
*. This is a lower bound of the true significance.

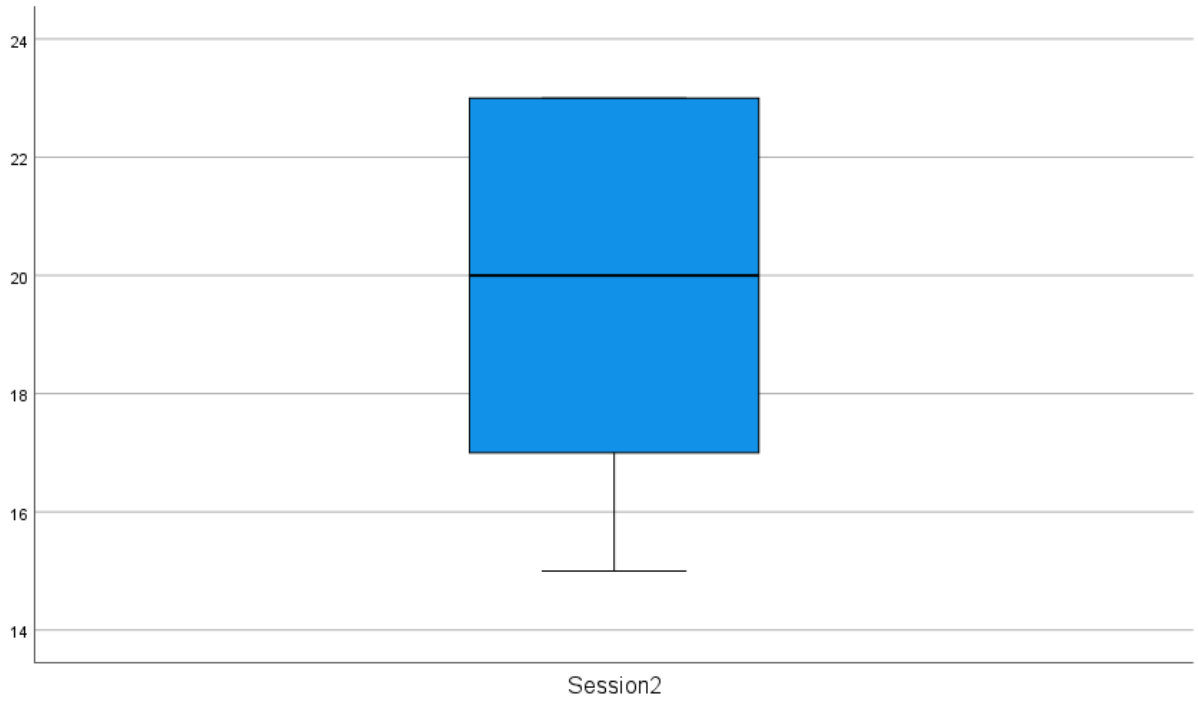
a. Lilliefors Significance Correction

Session2

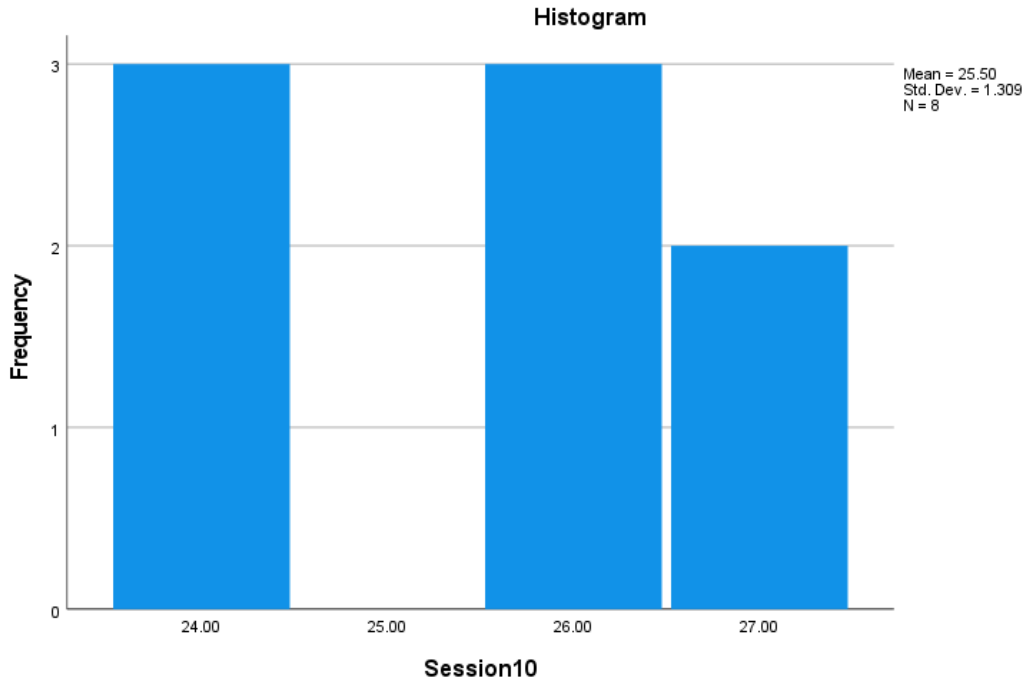


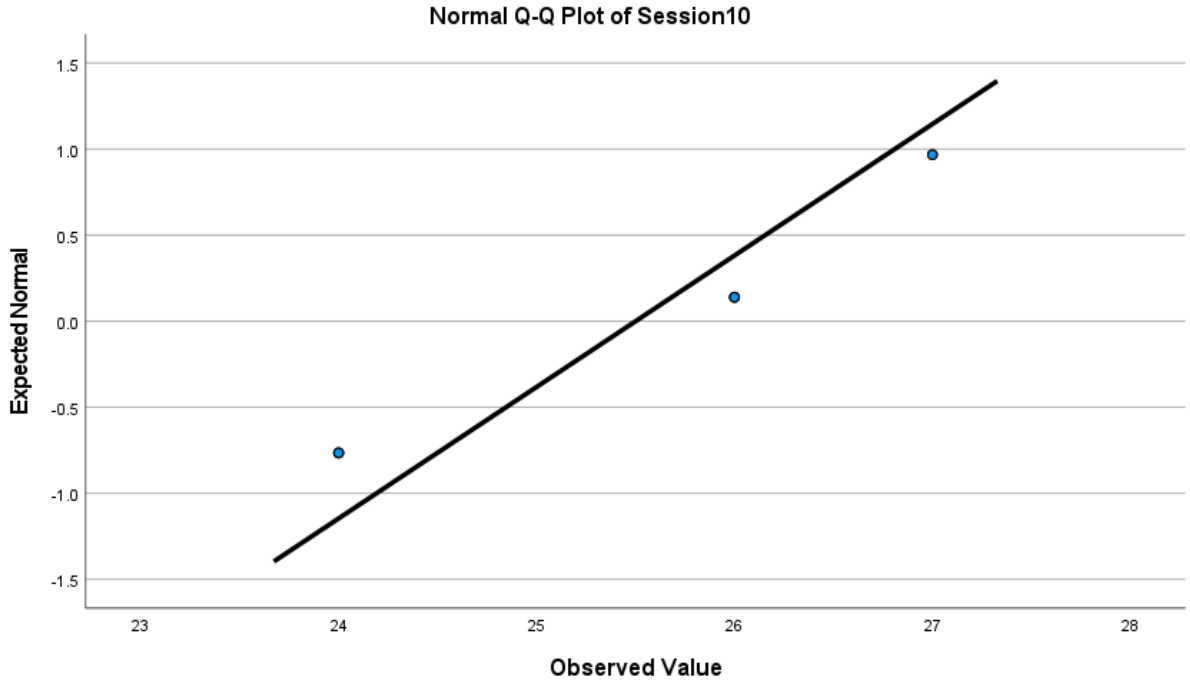

Normal Q-Q Plot of Session2
Expected Normal
2
1
0
-1
-2
14
16
18
20
22
24
Observed Value

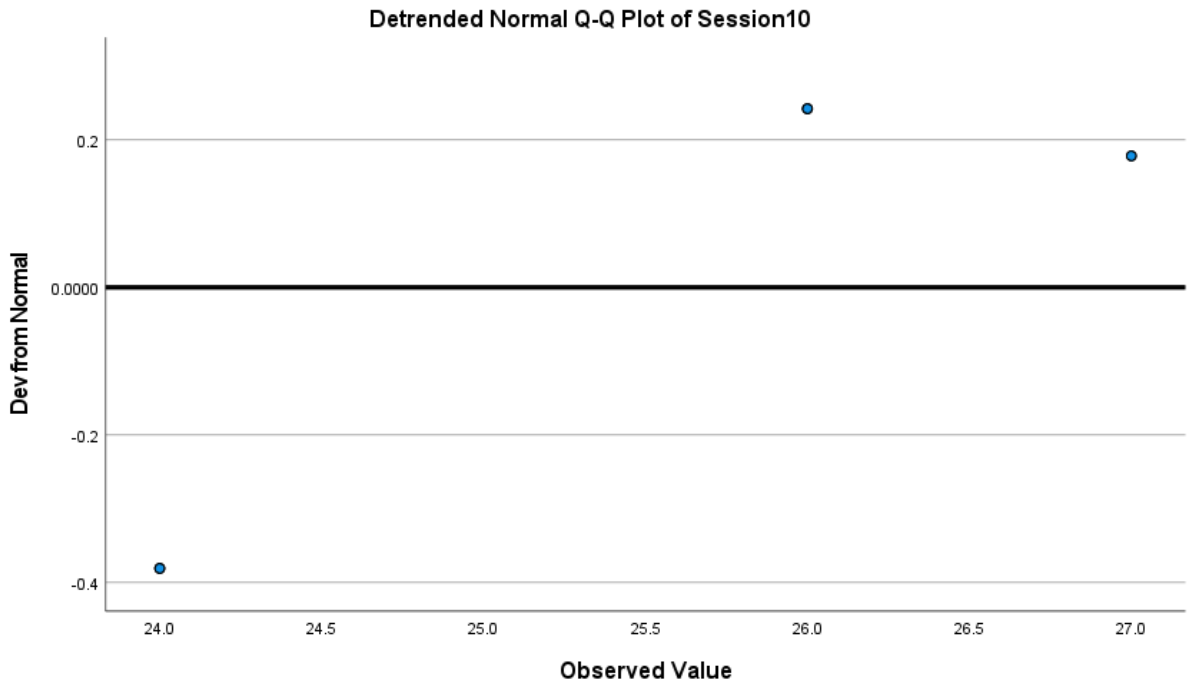

Detrended Normal Q-Q Plot of Session2
Dev from Normal
0.2
0.0000
-0.2
-0.4
14
16
18
20
22
24
Observed Value

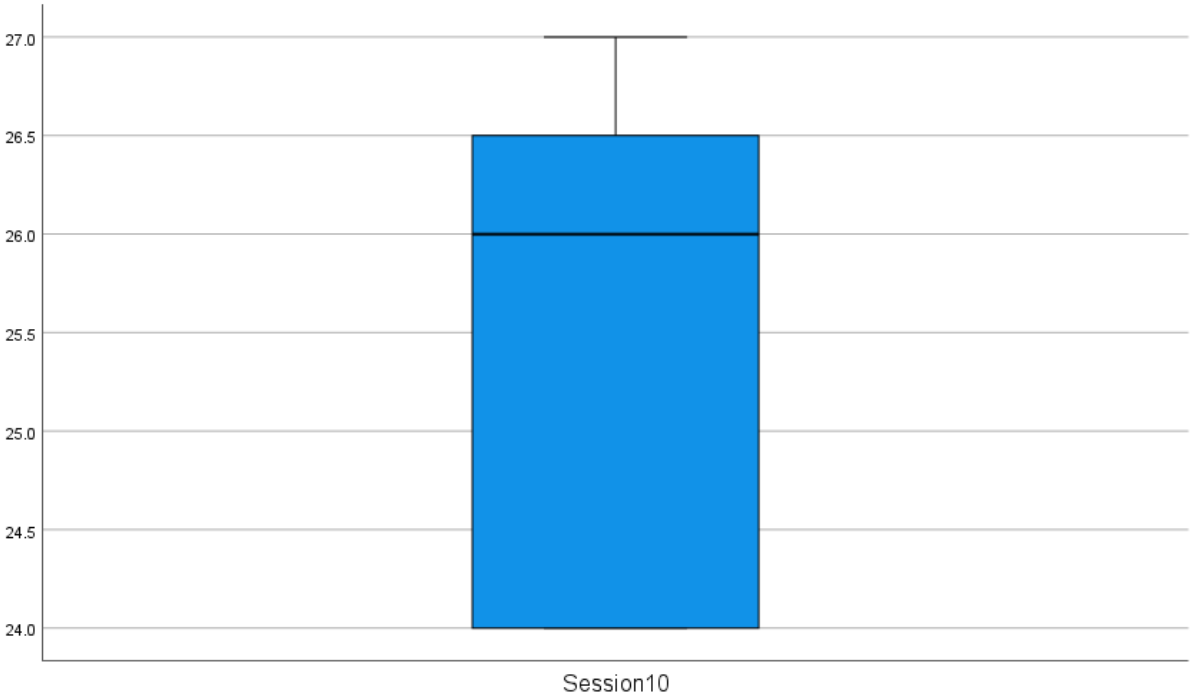


Session10


Histogram
Mean = 25.50
Std. Dev. = 1.309
N = 8
Frequency
3
2
1
0
24.00
25.00
26.00
27.00
Session10


Normal Q-Q Plot of Session10
Expected Normal
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
23
24
25
26
27
28
Observed Value


Detrended Normal Q-Q Plot of Session10
Dev from Normal
0.2
0.0000
-0.2
-0.4
24.0
24.5
25.0
25.5
26.0
26.5
27.0
Observed Value


27.0
26.5
26.0
25.5
25.0
24.5
24.0
Session10

```
NPAR TESTS
  /M-W= FCRS8 BY group(1 2)
```

NPar Tests

Notes

Output Created		18-JUL-2020 17:16:58
Comments		
Input	Active Dataset	DataSet2
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	16
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics for each test are based on all cases with valid data for the variable(s) used in that test.
Syntax		NPAR TESTS /M-W= FCRS8 BY group(1 2) /MISSING ANALYSIS.
Resources	Processor Time	00:00:00.00
	Elapsed Time	00:00:00.01
	Number of Cases Allowed[a]	449389

a. Based on availability of workspace memory.

Mann-Whitney Test

Ranks

	group	N	Mean Rank	Sum of Ranks
FCRS8	1.00	8	4.50	36.00
	2.00	8	12.50	100.00
	Total	16		

Test Statistics[a]

	FCRS8
Mann-Whitney U	.000
Wilcoxon W	36.000
Z	-3.393
Asymp. Sig. (2-tailed)	.001
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: group

b. Not corrected for ties.

```
FCRS9
EXAMINE VARIABLES=Session2 Session11
  /PLOT BOXPLOT HISTOGRAM NPPLOT
  /COMPARE GROUPS
  /STATISTICS DESCRIPTIVES EXTREME
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.
```

Explore

Notes

Output Created		18-JUL-2020 12:05:13
Comments		
Input	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	8
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.

Syntax		EXAMINE VARIABLES=Session2 Session11 /PLOT BOXPLOT HISTOGRAM NPPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE /NOTOTAL.
Resources	Processor Time	00:00:01.70
	Elapsed Time	00:00:01.12

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Session2	8	100.0%	0	0.0%	8	100.0%
Session11	8	100.0%	0	0.0%	8	100.0%

Descriptives

			Statistic	Std. Error
Session2	Mean		21.1250	.87500
	95% Confidence Interval for Mean	Lower Bound	19.0560	
		Upper Bound	23.1940	
	5% Trimmed Mean		21.1389	
	Median		21.5000	
	Variance		6.125	
	Std. Deviation		2.47487	
	Minimum		17.00	
	Maximum		25.00	
	Range		8.00	
	Interquartile Range		3.50	
	Skewness		-.190	.752
	Kurtosis		.131	1.481

Session11	Mean		28.7500	.67480
	95% Confidence Interval for Mean	Lower Bound	27.1543	
		Upper Bound	30.3457	
	5% Trimmed Mean		28.8333	
	Median		29.0000	
	Variance		3.643	
	Std. Deviation		1.90863	
	Minimum		25.00	
	Maximum		31.00	
	Range		6.00	
	Interquartile Range		2.50	
	Skewness		-.842	.752
	Kurtosis		1.550	1.481

Extreme Values[a]

			Case Number	Value
Session2	Highest	1	2	25.00
		2	5	23.00
		3	3	22.00
		4	6	22.00
	Lowest	1	8	17.00
		2	7	19.00
		3	1	20.00
		4	4	21.00
Session11	Highest	1	2	31.00
		2	7	31.00
		3	3	29.00
		4	4	29.00[b]
	Lowest	1	1	25.00
		2	8	28.00
		3	6	28.00
		4	5	29.00[c]

a. The requested number of extreme values exceeds the number of data points. A smaller number of extremes is displayed.

b. Only a partial list of cases with the value 29.00 are shown in the table of upper extremes.

c. Only a partial list of cases with the value 29.00 are shown in the table of lower extremes.

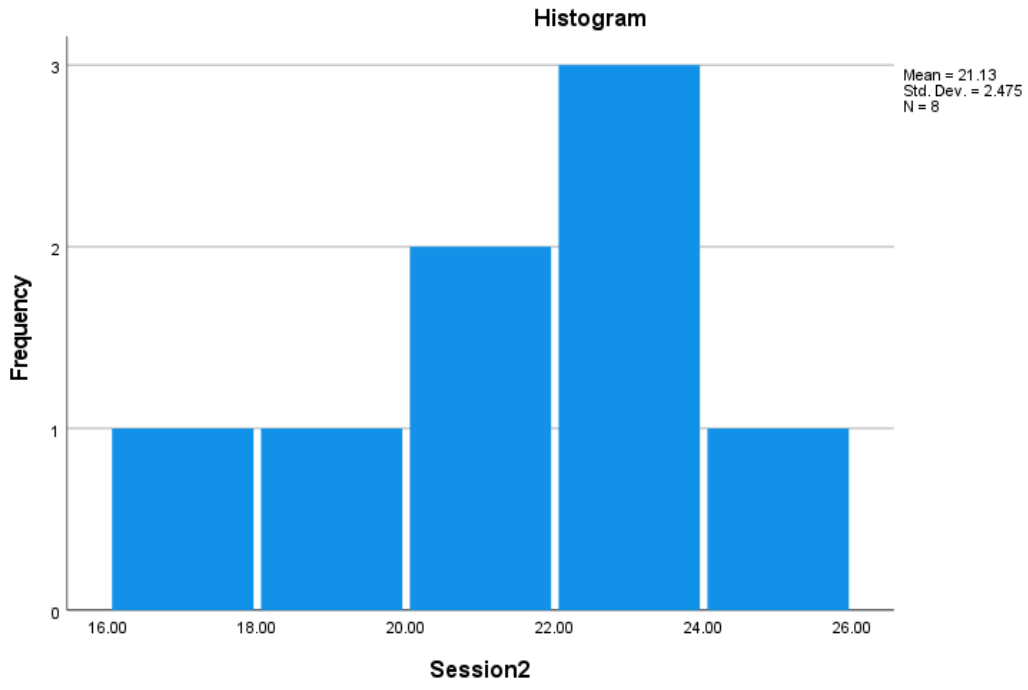
Tests of Normality

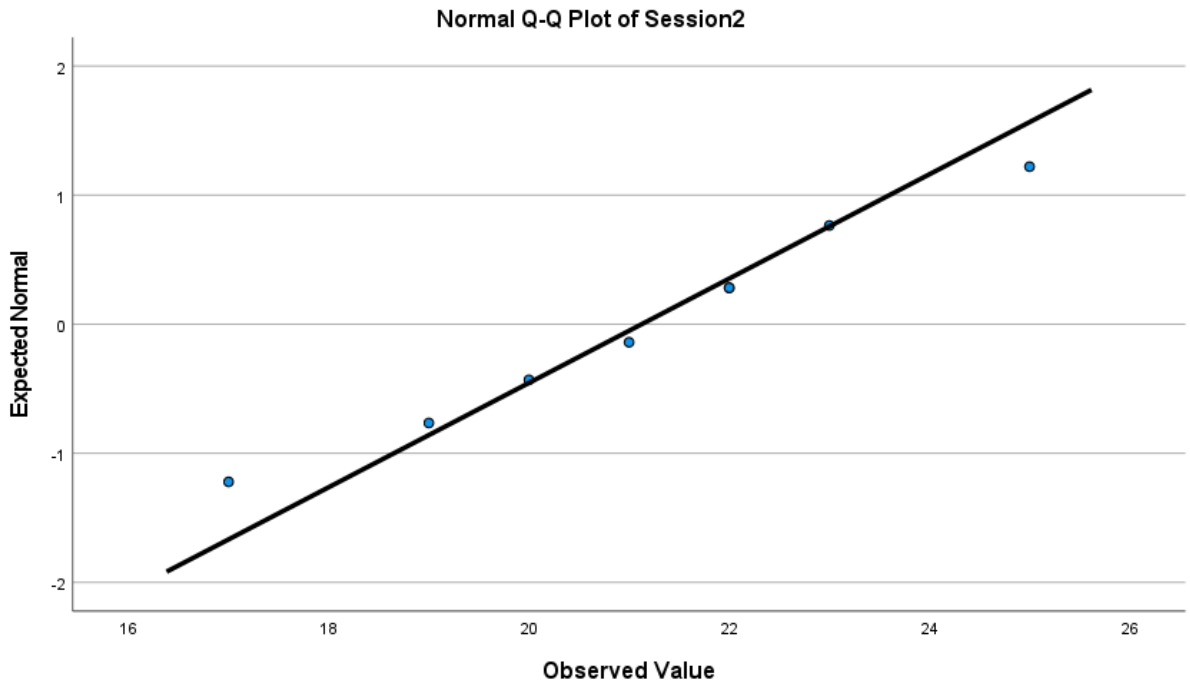
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Session2	.138	8	.200*	.989	8	.994
Session11	.222	8	.200*	.886	8	.217

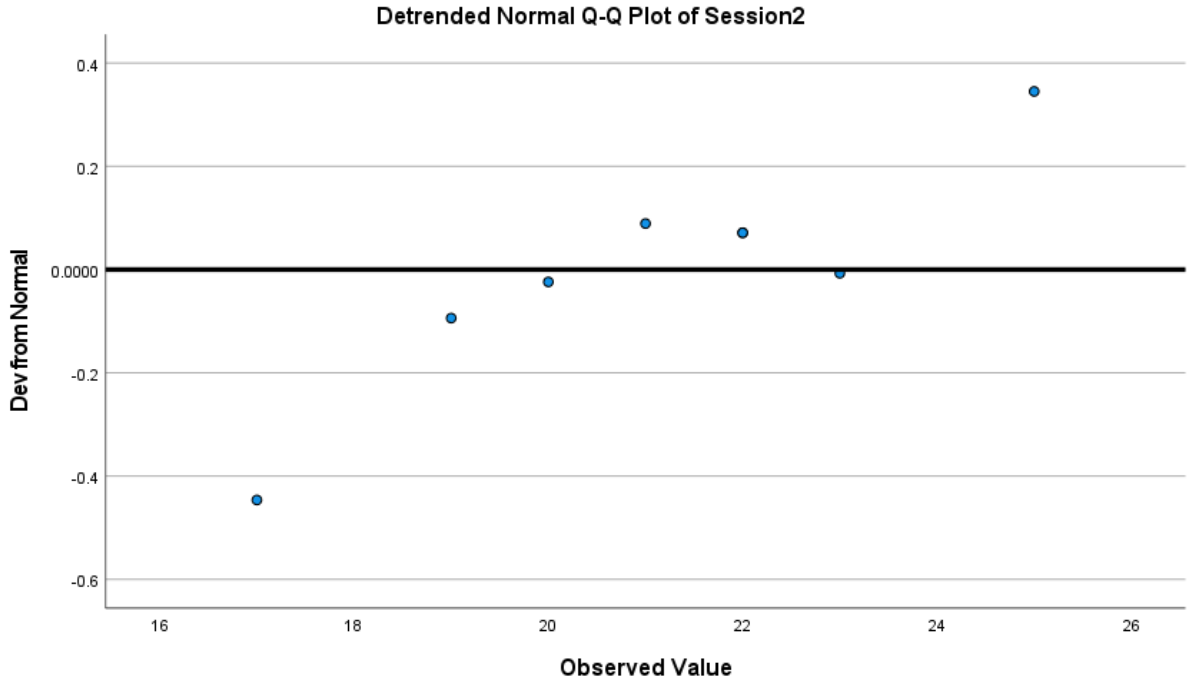
*. This is a lower bound of the true significance.

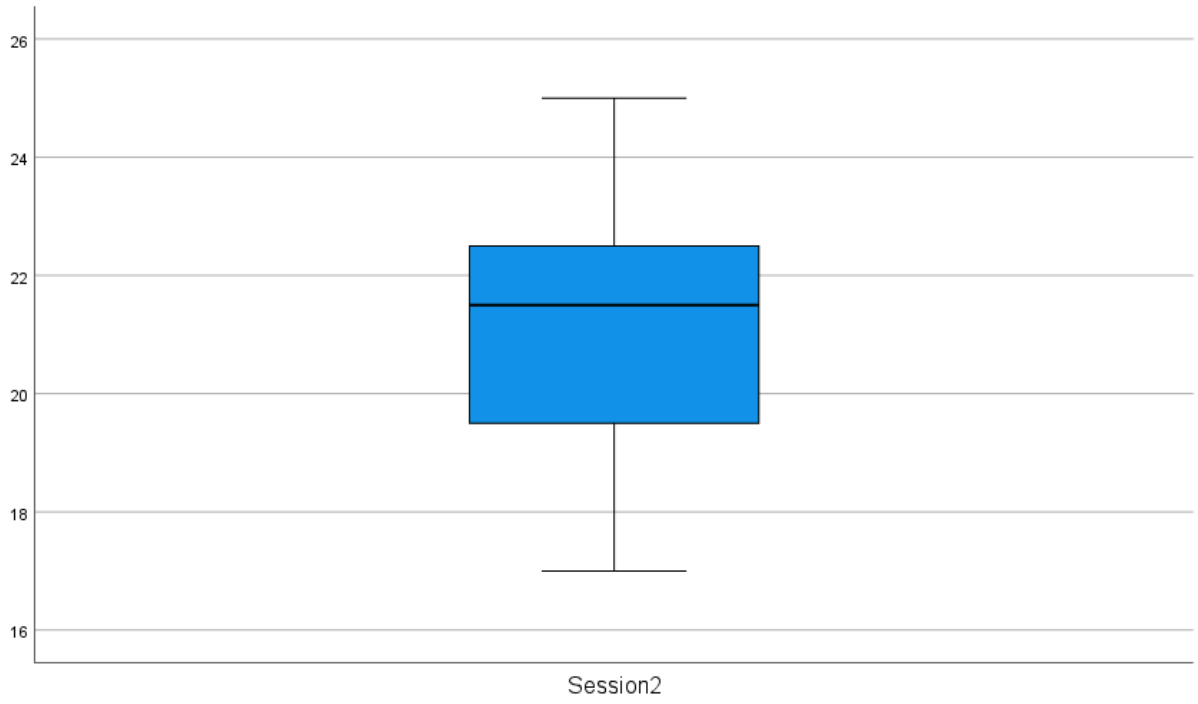
a. Lilliefors Significance Correction

Session2

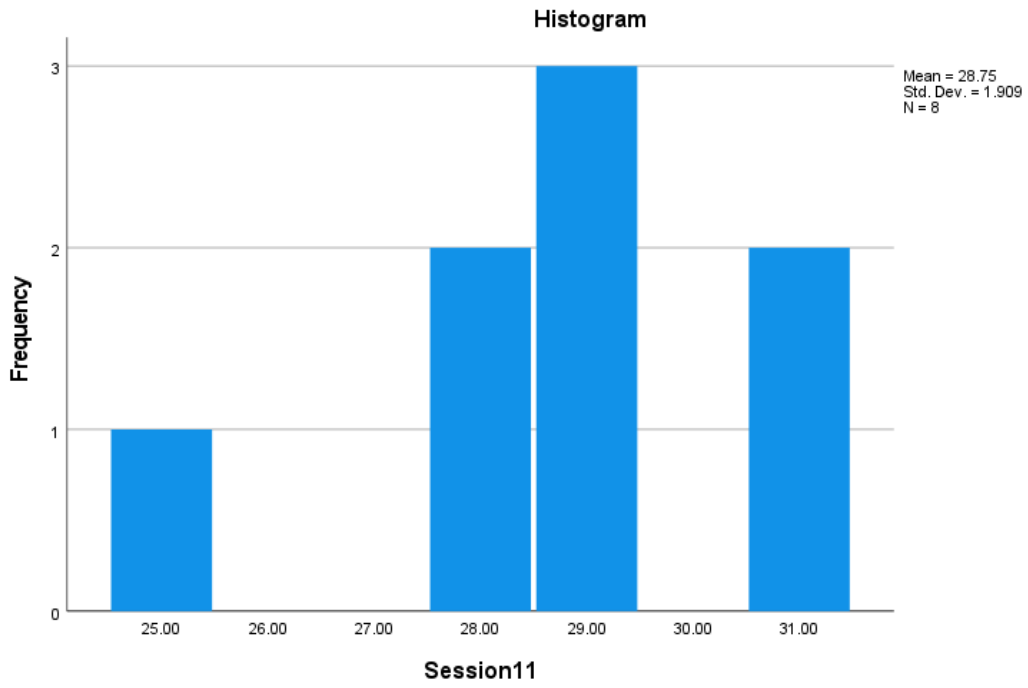


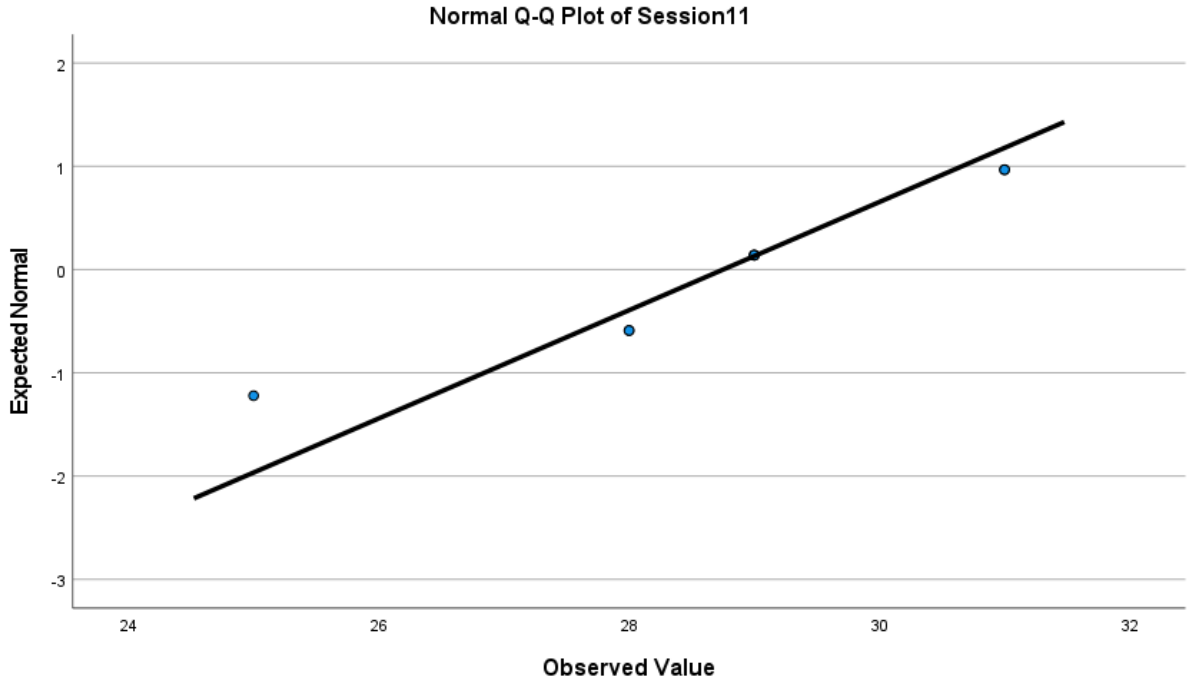

Normal Q-Q Plot of Session2
Expected Normal
2
1
0
-1
-2
16
18
20
22
24
26
Observed Value

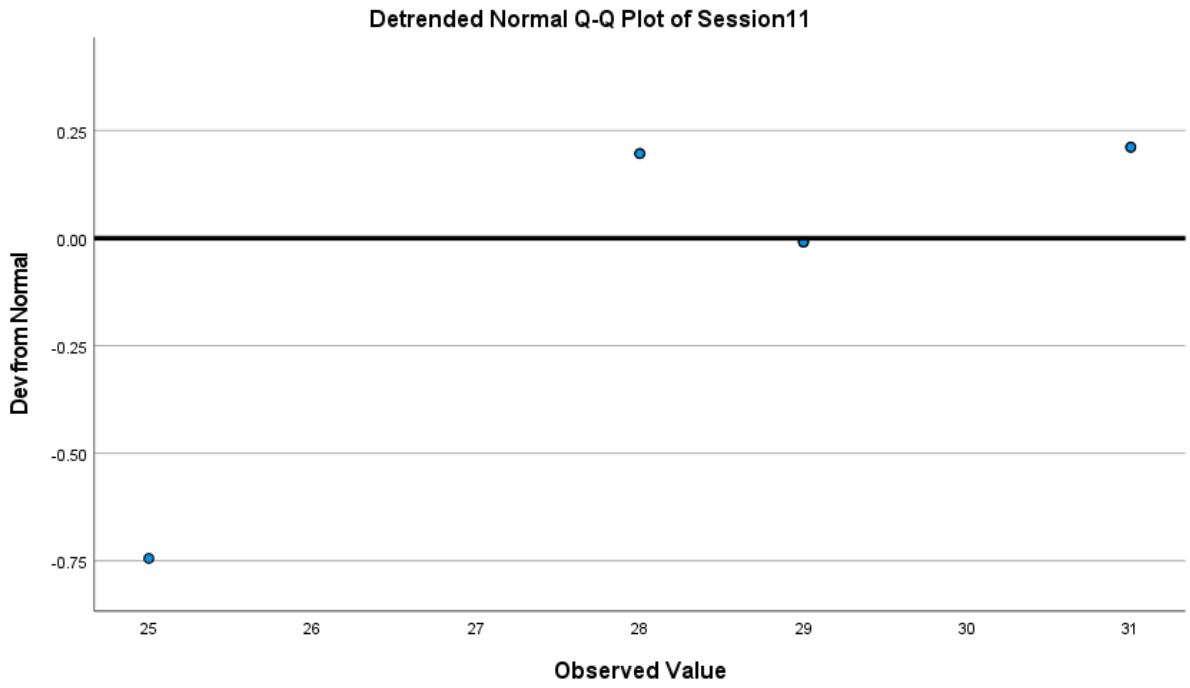

Detrended Normal Q-Q Plot of Session2
Dev from Normal
0.4
0.2
0.0000
-0.2
-0.4
-0.6
16
18
20
22
24
26
Observed Value

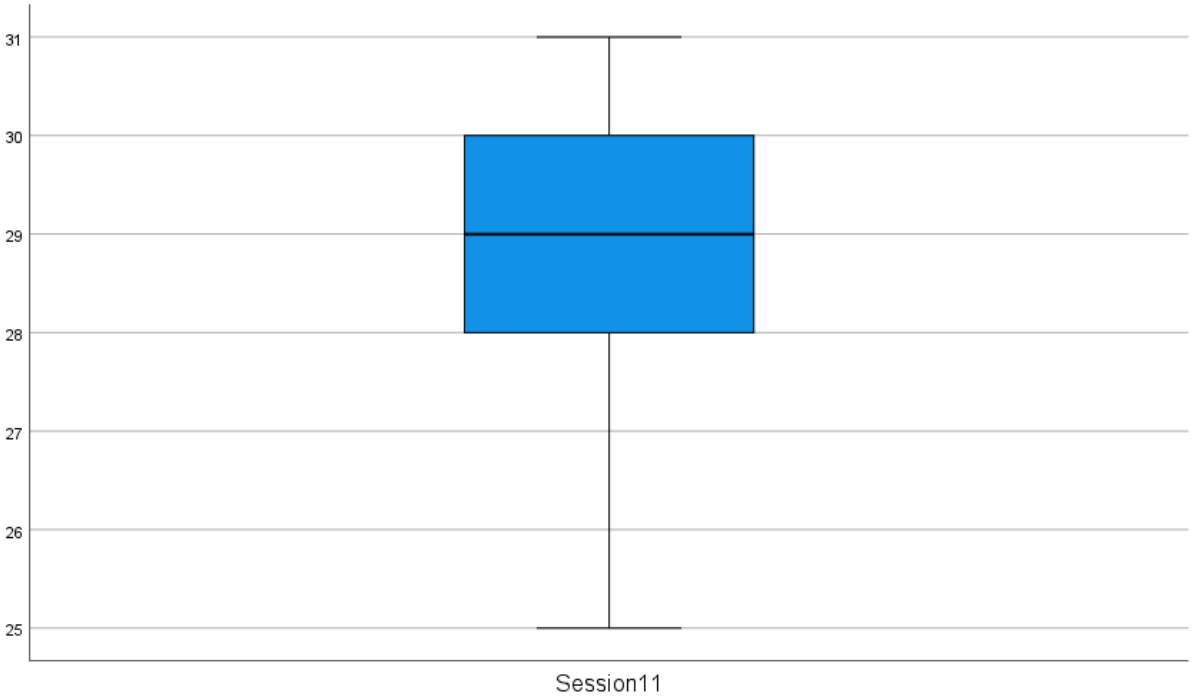


Session11


Histogram
Mean = 28.75
Std. Dev. = 1.909
N = 8
Frequency
3
2
1
0
25.00
26.00
27.00
28.00
29.00
30.00
31.00
Session11


Normal Q-Q Plot of Session11
Expected Normal
2
1
0
-1
-2
-3
24
26
28
30
32
Observed Value


Detrended Normal Q-Q Plot of Session11
Dev from Normal
0.25
0.00
-0.25
-0.50
-0.75
25
26
27
28
29
30
31
Observed Value


31
30
29
28
27
26
25
Session11

```
NPAR TESTS
  /M-W= FCRS9 BY group(1 2)
```

NPar Tests

Notes

Output Created		18-JUL-2020 17:18:36
Comments		
Input	Active Dataset	DataSet2
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	16
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics for each test are based on all cases with valid data for the variable(s) used in that test.
Syntax		NPAR TESTS /M-W= FCRS9 BY group(1 2) /MISSING ANALYSIS.
Resources	Processor Time	00:00:00.02
	Elapsed Time	00:00:00.01
	Number of Cases Allowed[a]	449389

a. Based on availability of workspace memory.

Mann-Whitney Test

Ranks

	group	N	Mean Rank	Sum of Ranks
FCRS9	1.00	8	4.56	36.50
	2.00	8	12.44	99.50
	Total	16		

Test Statistics[a]

	FCRS9
Mann-Whitney U	.500
Wilcoxon W	36.500
Z	-3.328
Asymp. Sig. (2-tailed)	.001
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: group

b. Not corrected for ties.