BRAIN TRAINING STRATEGY USING MOTOR IMAGERY

by

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ABSTRACT

People who suffer from motor disabilities have often a cognitively intact brain and are able to generate movement plans, but cannot realize such movement. These individuals could interact with the world through a Brain Computer Interface (BCI). Even though research into BCI has been conducted for many years, there is still no reliable product. We believe that the key to developing a reliable BCI is an adequate brain training strategy. This thesis studies an innovative training strategy for the control of a BCI using repetition of motor imagery, the thought of moving a body part without performing the movement. Repetition of motor imagery is investigated, in 5 participants differentiating right and left hand moving thought. The results show that reaction time happens at 0.6sec and that some people are able to train their brains successfully to reliably use a BCI, whereas others cannot achieve this goal.

Keywords: Brain, Training, Electroencephalography, Motor imagery, and Brain-Computer Interface

Subject Terms: Biomedical Engineering, Brain Training, and Brain Computer Interface

DEDICATION

Thanks to my parents and sibling, your love at the distance pushes me forward.

Thanks to my new family in Vancouver for you unconditional support in this new stage of my life.

Thanks to my friends, the laughter with you guys gives me the energy to continue.

Thanks to Travis, for being my other half.

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GLOSSARY

Brain-Computer Interface	(**BCI**) Communication device between a human brain and a external device
Electroencephalography	(**EEG**) Device that measures the electrical activity in the brain
Event-Related Potential	(**ERP**) An electrophysiological response to a stimulus
Matlab	A programming language created for easy use of matrixes manipulation, plotting, and other functions
Motor Imagery	The thought of moving a part of the body without performing the movement
Session	A EEG study, where a subject follows 50 motor imagery commands (trials) presented in a screen
Signal to Noise Ratio	(**SRN**) Ratio between the motor imagery EEG and the EEG signal at the relaxing stage
Trial	One thought of motor imagery

CHAPTER 1: INTRODUCTION

Nervous System

The human nervous system is highly complex and specialized. It is responsible for coordinating external stimuli and movement in the human body, allowing for motor skills and senses. Its unit is called neuron, composed of a body (soma), dendrites, and axon.

Neurons are interlinked and they communicate with each other by transmitting electrochemical signals through interchanging neurotransmitters in the synapse. The synapse is the location where two neurons communicate. The neurotransmitters are released commonly by the axons they travel through the synaptic cleft (the space between the axon and the dendrite) and then are received by the dendrites. The exchanges of neurotransmitters produce an electrochemical changes that are called action potentials. Typically the axon is in a resting voltage of –70mV. When an action potential is passing through, the voltage increases to approximately +40mV in one millisecond and then returns to the resting voltage.

There are different types of neurons; the ones located in the motor cortex, which is the area that we study in this project, are called Betz cells. They are pyramidal neurons that have a triangular shape. From their body, the apical dendrite, which is approximately 2mm, comes out ascending on the cerebral cortex overlaying with other cellular layers forming the grey matter. The axon

(15X10μm to 120X90μm) projects to other areas of the cortex and other structures sending feedback.

The nervous system is composed of two main parts: 1) the peripheral nervous system (PNS) and 2) the central nervous system (CNS). The PNS is composed of all the nerves. These nerves are axons that come out of the spinal cord and innervate the muscles, skin, and senses. The CNS is composed of the spinal cord and the brain.

The PNS is the connection between the human body and the external world, they are communicated by sensors, such as pain, vision, etc. When a sensor receives a stimulus, an impulse travels through the ascending nerves. It goes through the spinal cord or brainstem (CNS), and then connects to a neuron in the thalamus, whose axon travels to the cortical area where the senses are present in the cortex. At the cortex the neurons interconnect and a response to the stimulus travels through the descending nerves. They travel through the cerebellum and spinal cord, where nerves go directly to the skeletal muscles. When people suffer from motor disabilities, this communication is damaged at a certain level and therefore, the skeletal muscles and the brain do not communicate properly.

The most complex organ in the human body is the brain, part of the CNS. It is composed of the brainstem, the diencephalons, the cerebellum, and the cerebrum. The cerebrum is the most significant for the purpose of this study, because it is in charge of planning, controlling, and executing voluntary movements in the motor cortex.

The cerebrum is composed of six layers. The cerebral cortex is the outer layer, covering an area from 1500cm^2 to 3000 cm^2 and with a thickness between 2mm to 5mm *(1)*. It is composed of 6 distinct layers, which differentiate from each other from the types of neurons and the organization of the axons. As mentioned earlier, the neurons in the cerebral cortex form grey matter. A deeper layer under the cortex, composed of axons, forms the white matter. The grey and white matter form structures called gyri (ridges) and sulci (valleys).

The brain is divided into 2 hemispheres, left and right, separated by the central fissure. The two hemispheres are similar in shape and functionality, though some functions are localized in a certain hemisphere. Each hemisphere is divided into 4 lobes, which are divided by fissures. Such lobes are:

- *Frontal lobe*, localized in the anterior part of the cerebrum and responsible for speech, emotional behaviour, and voluntary movement. The gyrus closest to the central fissure is where the voluntary movements are localized. Lesions in this area cause partial paralysis on the opposite side of the body.
- *Parietal Lobe*, localized in the posterior part of the cerebrum, responsible for sensing touch.
- *Temporal lobe*, localized on the sides of the cerebrum, responsible for the auditory system.
- *Occipital lobe*, localized at the back of the cerebrum, responsible for vision.

Electroencephalography (EEG)

As mentioned earlier, the brain produces electrical activity (action potentials), which can be recorded with an EEG system. The specific sources within the cerebral cortex of the electrical activities that are recoded on an EEG system are not certain. It is believed that the action potentials recorded on the EEG are the voltage changes from the extra-cellular space and not form axons and/or dendrites of neurons.

The action potentials travel through the skull and reach the scalp with amplitudes between 20μV to 200μV if the reference point is the earlobe. These signals have a varying frequency of between 0.5Hz to 100 Hz. These are called brain waves. A conventional EEG signal is presented in Figure 1-1 to illustrate how the brain activity is seen using this device.

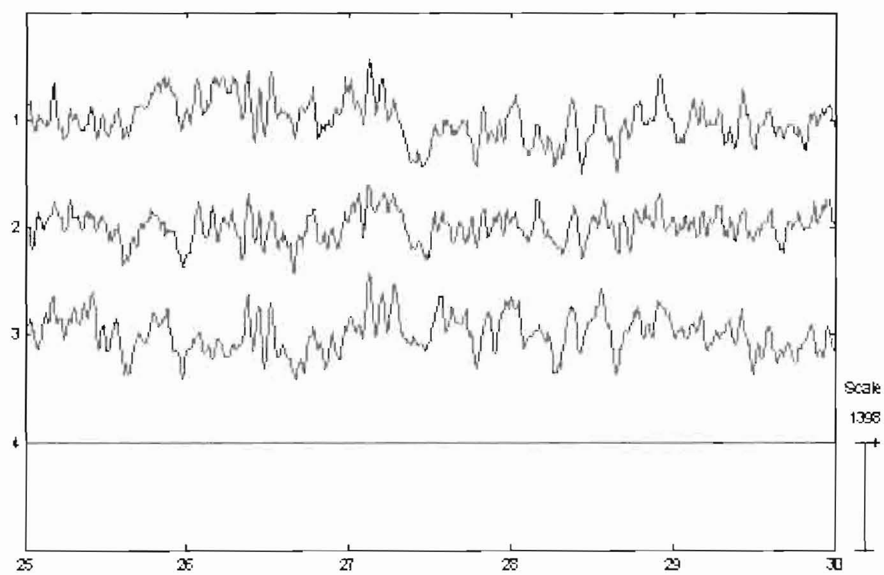


Figure 1-1: 5sec of EEG signal

Brain waves vary depending on the degree of activity of the cerebral cortex. Table 1-1 presents the EEG waves *(2)*.

Table 1-1: EEG brain waves

Signal	Frequency (Hz)	Generally found in:
Delta	0 to 3.5	Adults in deep sleep and infants.
Theta	4 to 7	Infancy and childhood. Adults in state of drowsiness and sleep.
Alpha	8 to 13	Healthy relaxed adults and with closed eyes.
Beta	14 to 30	Mental activity.
Mu	7 to 11	Alpha waves with higher amplitude, approximately 50μV.
Gamma	30 to 40	Occur when deep concentration is obtained.

The EEG is composed of: electrodes, amplifiers, filters, analogue-to-digital converter (ADC), and a recording, processing and display device *(3)*.

The electrodes are placed on a clean scalp. This connection needs to have small impedance with respect to the amplifier input resistance. The EEG signal is collected on channels; each channel is the difference between two electrodes with the purpose of obtaining a common mode rejection signal *(4)*. The channels can have several set ups, called montages.

A bipolar montage is when a channel is the difference between adjacent electrodes, and is the one used in the present study. The location of the electrodes on the scalp vary depending on the application, the most common one is called 10-20 System.

The amplification of the signal is done in two stages. The first one is a differential amplifier, where the signals go directly from the electrodes. Voltages from a pair of electrodes are subtracted and obtain a gain of approximately 20. The second amplification is done after the filtering of the signal (gain of 10,000 to 20,000).

Filters are needed to obtain a clean EEG signal. A notch filter eliminates the power line frequency (60 Hz), and there is also a band-pass filter allowing only the desirable frequencies to pass. These filters are currently done digitally, and the user can adjust the cut-off frequency.

The brain signals are obtained analogue and the display, processing, and storing is done digitally, hence the need for ADC. The resolution varies depending on the system. Sampling rates commonly are between 256-512 Hz for medical purposes, but they can go up to 10 kHz for research.

The digital process, data display, storage, and analysis are conventionally done through a computer. Here, several operations can be done to the EEG signal, such as: filtering, calculating different montages, changing the scale and colour, arrange the channels in different orders, measuring amplitude and period duration with interactive cursors, marking several events, saving data, and evaluating the data at any future time.

The EEG signal can be analysed visually or by using an analysis program. An analysis programs include tools to make a quantitative analysis of the data, such as spectral power analysis, pattern detection, and correlation, among others.

Event Related Potential (ERP)

As explained earlier, when a stimulus from the external world strikes a sensor in the body, neurons fire action potentials. Event related potential, as its name suggests, is the recorded action potential of the neurons as a response of an external event (or stimulus). Different types of events can be presented, such as visual stimulus, audio stimulus, etc. This study, as well as many others, is based on visual ERP *(5)*.

Brain-Computer Interface (BCI) background

People who suffer form motor disabilities caused by spinal cord injury, muscular dystrophy, locked-in syndrome, or other origin, have a decreased or non-existent communication between the muscles and the brain. Still, they often have a cognitively intact brain and are able to generate movement plans, but they cannot realize such movement. These people could interact with the world through a BCI.

There is no standard design for a BCI; each research group approaches different methods throughout their device. Although, all BCI are composed of essentially the same components: an acquisitions method, a signal, a signal processing/analysis, an output, and a training process. Every component has several possible applicable techniques, which are discussed below.

The fist component of a BCI is the acquisition method, in which the signal is obtained. The acquisition methods can be divided into two broad classifications: invasive and non-invasive. The invasive methods have two alternatives: the single neuron recording and electrocorticographic. The first one consists of a neurotrophic electrode implanted on a single neuron *(6)*. The second one is an implanted electrode on the sub cortical or extra cortical, subdural or extradural area of the brain, recording the activity of several neurons in one area *(7-9)*.

The non-invasive methods that record brain activity are: functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and EEG. EEG is the most common signal acquisition method because it is non-invasive, cost effective, and portable to a certain extent. On the other hand, EEG permits flexibility of electrode numbers and arrangements, allowing to obtain different signals.

The second component is the signal, which depends on the acquisition method used. In the single unit recording method, the action potential of such neuron is the signal. In the electrocorticographic method, the local field potential is recorded. The signals obtained from the EEG are mainly rhythm amplitudes, evoked potentials, slow cortical potentials, and ERP.

ERP is commonly obtained by motor imagery, which is carried out by thoughts of performing a body movement without executing it. Usually limb movement (e.g. thinking of moving the right hand without actually moving it). Motor imagery is found to be stronger in the contra lateral hemisphere of the brain *(25)*.

The signal processing is the third component and the one with more possible approaches. Some of the different signal processing methods are:

- Averaging a number of EEG segments registered from a stimulus obtained from an evoked potential signal *(10)*.
- Adaptive auto regression (AAR), which recognizes a pattern in the EEG. AAR calculates parameters for each iteration using a recursive algorithm with the least squares *(11-15)*.
- Distinction sensitive learning vector quantization (DSLVQ), which determines the most significant frequencies by weighting distance function and, adjusting frequency components *(13)*.
- Low-frequency asynchronous switch design (LF-ASD), which calculates a 6-dimension vector, recognizing a voluntary movement and obtaining a transformation function *(16, 17)*.
- Spectral analysis, which transforms a spatial filter window to the frequency domain. An estimation of auto regression provides coefficients forming a vector *(18-21)*.

At the same time, the signal processing holds other characteristics that are interlinked with the chosen analysis method and the researchers design. Such characteristics are: if the transformation of the signal to a command is linear or non-linear, adaptive or non-adaptive, if there is on-line analysis or off-line analysis, and if the process integrates an error correction algorithm or not.

The output is the component of a BCI that lets the user communicate with the external world and/or manages their environment. The most common outputs are cursor movement, letter or icon selection, and command to a device. Some outputs can be designed in one dimension or in two dimensions. Simultaneously, all the outputs can be continuous or discrete. The output for research purposes is usually real-time feedback the user receives from their EEG signal.

Training is the last component of a BCI and the least documented one. Only in recent years have researchers been paying more attention to the training process, but it is not clear how much focus is put to this component. Documentation about training usually takes up few lines in an article if any at all *(5, 21)*.

In training the brain, the individual learns to control the brain's energy level (frequency and amplitude). The signal of the brain changes depending on the person's predominating brain wave and mental state, e.g. slow pulses are produced by creative and intuitive thinking, fast ones by logical and rational thinking, and middle speed pulses are obtained in the awareness state *(22)*.

Training process is mainly categorized in cognitive (mental effort to control the device) and behavioural (no mental effort to control the device) processes. The cognitive procedure consists of mental effort while learning to use the device. The user is asked either to move a limb or have the thought of moving such limb to obtain the desired output. Some researchers have used different thoughts such as, thinking of words that start with a specific letter, mathematical exercises, visual counting, and geometric figure rotation *(23)*.

A few researcher's groups have the impression that most training processes start with the cognitive method, because after a certain time, mental effort is not necessary and the brain gives a command to the BCI in a behavioural manner *(23)*. The Wadsworth Center's research group have doubts about the intellectual and cognitive methods being enough to successfully use a BCI *(24)*. They suggest that a behavioural analysis should be as important.

Motivation

A high probability that the reason why there is no reliable BCI is because researchers are putting most of their effort and focus into the signal processing and are ignoring the source of the signal, the brain.

BCI research based on motor imagery assumes that the brain can be trained using motor imagery in a successful manner such that the output of an EEG can be used as a command for a BCI *(12, 15, 25-27)*. As shown, there are enough studies that base the BCI research in motor imagery, but no study has done over 100 motor imagery repetitious in more than 3 subjects.

The assumption that motor imagery remains strong after several repetitions could be false because of brain plasticity *(22)*. For example, when we learn a skill like walking, we start by concentrating and paying close attention to our movements. Once we master these movements, we can then walk without the previously needed concentration or effort. Walking becomes an automated movement and later on we can do other activities at the same time as we walk because our brain does not need to concentrate so hard on walking.

This same process could happen with motor imagery. This means that the original ERP response obtained in the first few trials of performing motor imagery might change or disappear from the motor cortex with repetition of motor imagery because the brain has automated these thoughts.

The problem encountered is the uncertainty that the brain can be trained to use motor imagery in a useful way for BCI. This would have a great impact, because if the motor imagery brain training is successful, EEG signals can be used as control data for BCI. If training is unsuccessful, BCI has to use other types of EEG responses as control data.

Objectives

The main objective of this study was to determine if after many repetitions of the same motor imagery the EEG signal was reliable enough to be used as a command signal for a BCI. 3 components were the focus in the present study: reaction time, ERP of the motor imagery, and difference between right and left motor imagery, all after visual stimuli.

The first component is reaction time and the objective is to quantify if the motor imagery response time becomes faster or remains constant after many repetitions. If the response time decreases, the possibility of automation is present. If the time response stays the same, it means that it will be present and reliable at a given moment. We anticipated that the response time would not increase since this would mean that the person is responding slower to the stimulus.

The objective of the ERP analysis was to quantify the correlation coefficients of the trials and determine if the signal changes over time. If after repetitions the correlation values remained constant, this would mean that the signal is reliable and can be used as a BCI. If the correlation values increased, the EEG signal is chaining with repetition and training is happening. If the correlation values decreased, it means that the EEG signal is being lost and is becoming automated.

The third component was the difference between right and left. The objective was to quantify how different the motor imagery between right and left are in the 2 hemispheres of the brain while doing right and left motor imagery.

Signal to Noise Ratio was computed to evaluate the difference between right and left and to complement the results in evaluating how the EEG signal changes over repetitions of motor imagery.

CHAPTER 2: METHOD

Subjects

The study was done with participants of different ages and backgrounds, with the purpose of having a variety of mentalities and problem solving approaches. Five subjects participated in the study. 1) a male in his mid-fifties with a background in sciences and with previous experience in motor imagery, 2) a female in her early sixties with a teaching background, 3) a male in his early twenties with a geography background. 4) and 5) were males in their twenties with backgrounds in sciences, one if them with previous experience in motor imagery.

All subjects filled a pre-screening questionnaire in order to maintain minimal risk (such questionnaire addressed anxiety disorders, health history, intake of mentally altering substances, and practice of meditation), and signed a consent form before starting the data acquisition.

Equipment and setting

Electrodes placement

The electrodes were placed on the subjects' scalp in the motor cortex area. The motor cortex is located above the ears and it is responsible for planning, controlling, and executing voluntary motor functions. We are assuming that the left and right hemispheres at the motor cortex level are similar in their functions to control voluntary movement of hands.

Three sets of electrodes were placed using a bipolar combination, Cz forming channel 1 (centre), C3 forming channel 2 (left hemisphere), and C4 forming channel 3 (right hemisphere), according to the 10-20 System, see Figure 2-1.

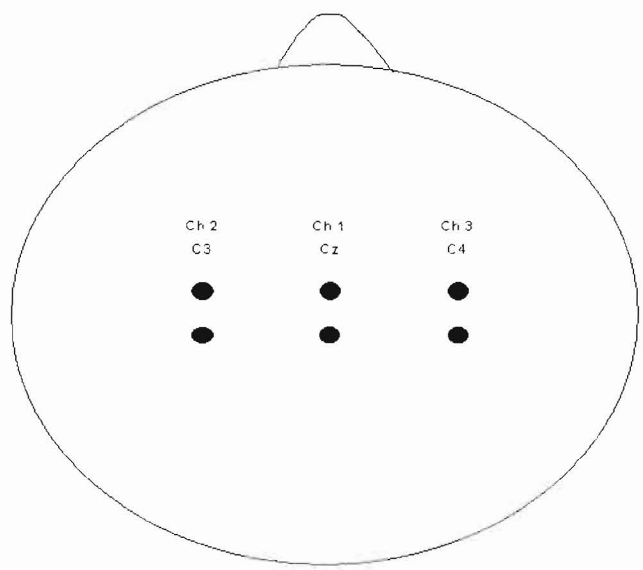


Figure 2-1: EEG channels used in this study

Also, reference electrodes were placed at A1 (left ear), A2 (right ear), and Z (forehead) for impedance and acquisition referencing purposes. The small impedance between the scalp and the electrodes was checked before each data acquisition to assure proper electrodes placement *(3)*. The impedance was between 0.5 and 0.9KOhmns.

Before placing the electrodes, measurements of the heads were done in order to be consistent with the location of the electrodes. The hair was moved to the side, the scalp was cleaned with alcohol, and conductive paste was put on the electrode previous to placing it on the scalp.

Subjects setting

The experiment was done inside a metal-wall-shielded room that blocks light, sound, and stray signals. The lights inside the room were turned off while data was being acquired. Only the researcher and the subject being tested were in the shielded room during data acquisition.

Inside this room, the Nihon Kohden EEG-2110 System was located next to a comfortable chair where the subjects sat, with support for their arms and head. A screen (27cm x 16cm) was placed approximately 60cm in front of the subjects, at the head level, where the visual stimuli were presented. The researcher was sitting on a chair in front of the EEG monitor.

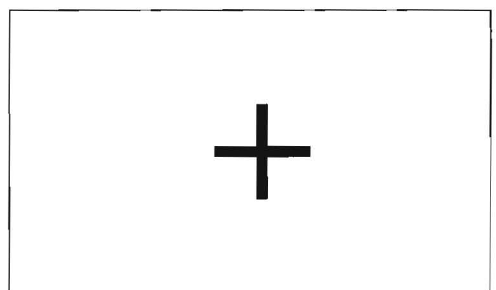
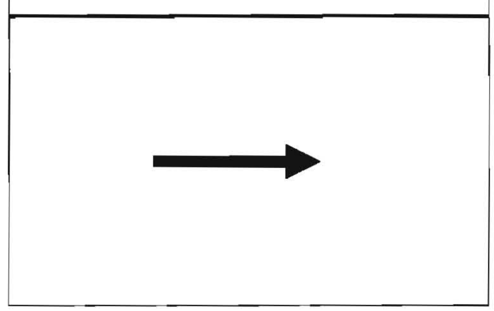
The subjects were asked to relax and to remain still while the data was being acquired. A sequence of signs appeared on the screen in front of them. This protocol is discussed in the next section. After the sequence was finished, the subjects had time to relax and afterwards a second data acquisition was obtained. At the end of the second data acquisition, the electrodes were removed from the subjects' scalp.

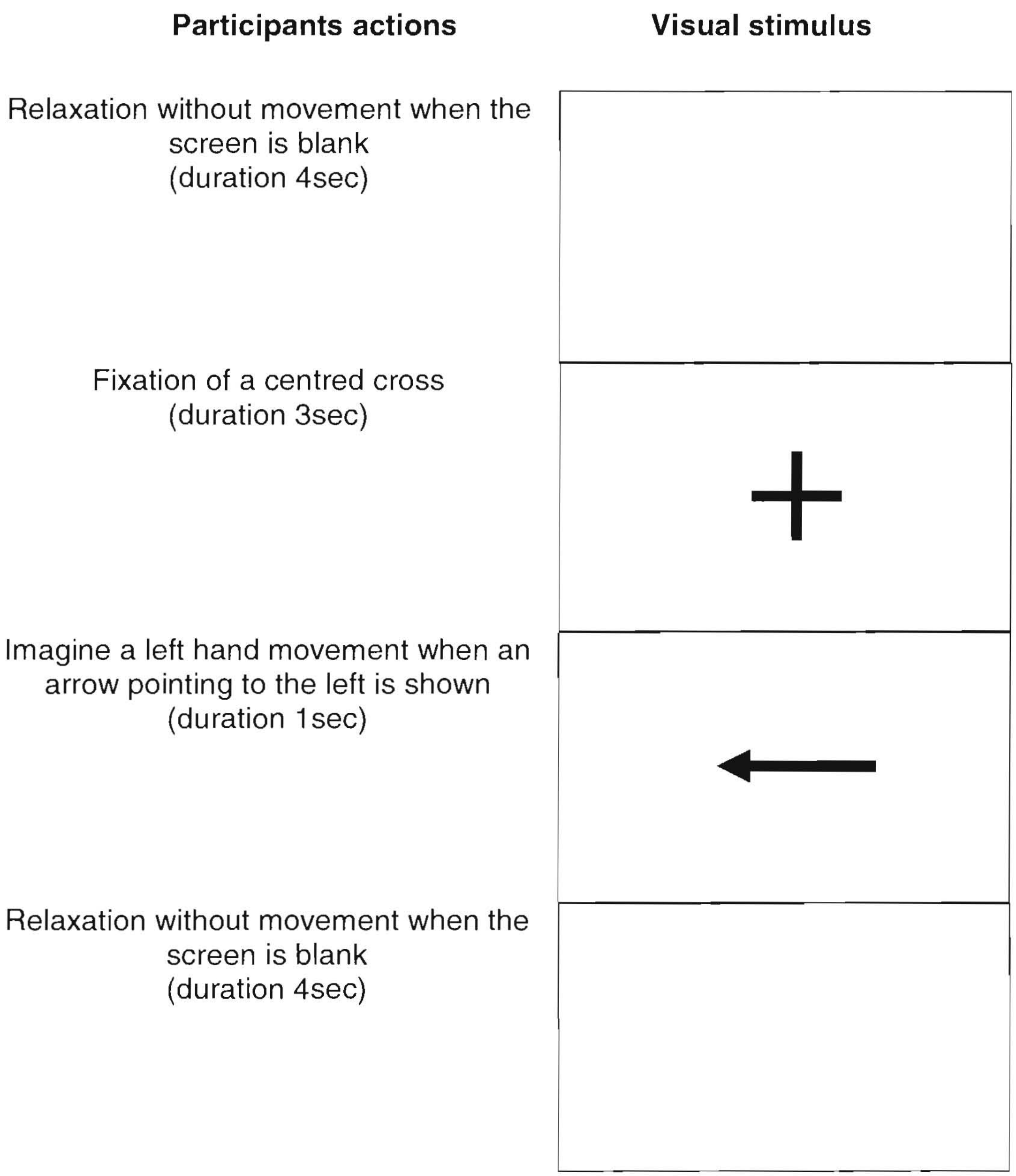
Procedure

Each subject visited the research laboratory approximately two times a week for a period of 5 weeks. On each visit, two sessions were performed. Each session consisted of a sequence of 50 trials, 25 to the right direction and 25 to the left; the direction was random to avoid anticipation.

One trial is a visual stimulus where the subject is asked to do motor imagery, and it is composed of a fixation cross, an arrow, and a relaxing period. Table 2-1 illustrates the participants' actions and the symbols that represent the visual stimuli. Each session lasted 6.66min.

Table 2-1: Examples of 2 trials form the protocol

Participants actions	Visual stimulus
Fixation of a centred cross (duration 3sec)	
Imagine a right hand movement when an arrow pointing to the right is shown (duration 1sec)	



Data acquisition

The EEG system settings were as follows: sampling frequency at 200Hz, sensibility at 1μV/mm, and high cut-off frequency filter at 30Hz.

While the participants were doing the sessions, the EEG was saving the data. All the data was configured to the channels mentioned above and then transferred to a laboratory computer. The data was processed and analysed off-line, after all the data was collected.

Before the first data was acquired, one session was done with the intention of familiarizing the participants with the procedure and the motor imagery exercise. At the same time this gave participants the opportunity to ask questions, minimizing possible errors on the study.

Subjects were asked to document their experience of the study after the third or fourth session and at the end of the study. These comments are used for analyzing the data and can be seen in Chapter 3.

Data processing

The data was organized under subject, session, direction of motor imagery, channel, and trials. All the data was analysed and saved under this structure. Data among different directions, channels, and subjects were never mixed. View appendix 10 for the Matlab codes.

Using EEGLAB (a Matlab script), the data was opened and filtered with a low-pass filter, cut-off frequency at 30Hz. Later, the sequence of symbols was marked along the EEG signal and the locations of channels were defined at the EEGLAB. Refer to appendix 9 for an illustration.

Each trial was extracted and isolated using a window of –1sec and +2sec before and after the arrow visual stimulus. Then the trials were categorized in left and right. The average ERP of the last session was computed (from now on we will refer to this as a pattern). The pattern is considered important data because by comparing it with the rest of the sessions, conclusions about training were extracted. Since there are 2 directions, right and left, and 3 channels, 6 pattern signals are computed for each subject:

- **Pattern 1 (right)** consists of:
  - Pattern 1 from channel1
  - Pattern 1 from channel 2
  - Pattern 1 from channel 3
- **Pattern 2 (left)** consists of:
  - Pattern 2 from channel1
  - Pattern 2 from channel 2
  - Pattern 2 from channel 3

Cross-correlation was computed between the 500 trials from all the sessions and the corresponding patterns using Equation 2-1 *(39)*. All correlations were consistent in using the corresponding pattern and trials.

$$R_{xy}(m) = \sum_{n=0}^{N-m-1} X_{n+m} Y_n$$

Equation 2-1: Cross-correlation formula

Where N=500 trials, m=(N*2)-1, X=pattern, and Y= trials. The cross-correlation out-put presented a high frequency signal and the interest in the study was the highest correlation value. To obtain the maximum data point, which is the highest correlation value, the data was filtered using absolute values of

Equation 2-2 *(39)* that presents the input-output explanation of the filtering operation.

$$Y(z) = \frac{b(1) + b(2)z^{-1} + ... + b(nb+1)}{1 + a(2)z^{-1} + ... + a(na+1)Z^{-na}} X(z)$$

Equation 2-2: Filter formula

A window size of 50 data points was used. This covers two negative and positive peaks; windows sizes between 20 and 70 gave very similar results.

From the filtered cross-correlated data, two measurements were extracted and saved on a variable: maximum correlation, and the data point when such maximum value occurred, which represents time. On Figure 2-2, the illustration shows the maximum correlation value at $4.9X10^5$ at 610 data points, which later is converted into time and is the measurement for reaction time.

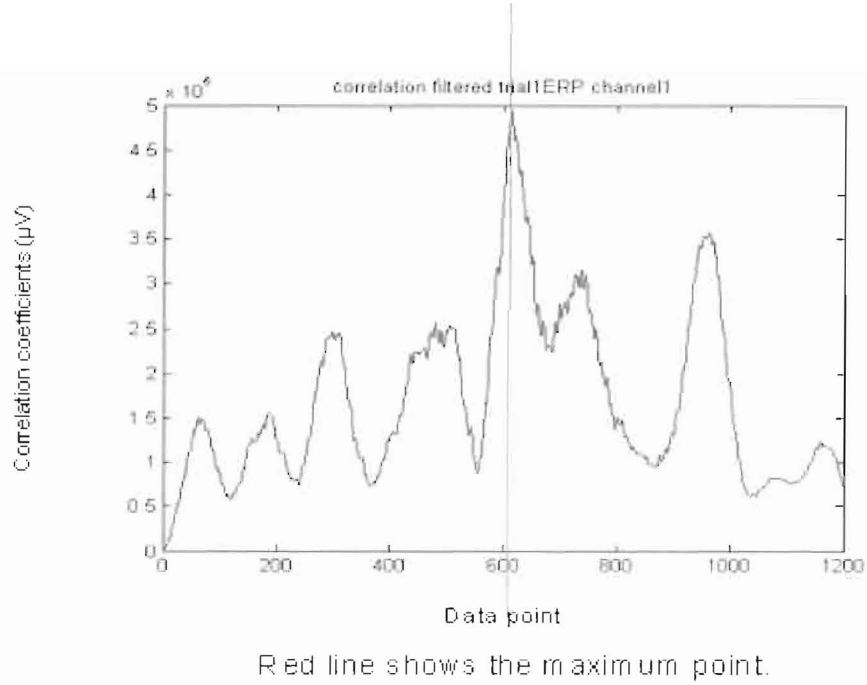


Figure 2-2: Illustration of the filtered correlation coefficients

The data points that represent time were converted to seconds. Every 400 data points of the cross-correlation out-put form 1 sec, therefore Figure 2-2 has the 3 seconds that were analyzed, being the visual stimulus at 400.

Next the variables that contain the correlation coefficients and reaction time data from each session were concatenated and organized from 1 to 500 trials. At this point there are 12 groups of data for each subject, each with 500 points, 6 for correlation coefficients and 6 for reaction time, where 3 are from each channel on the right and 3 from the each channel on the left.

To analyze the data's evolution through repetitions two methods were computed, 1) least square mean and 2) signal-to-noise ratio (SNR).

Least square mean modeled the obtained data to a 3rd degree polynomial, see Equation 2-3 *(39)*, correlation coefficients and the reaction time were fitted.

$$P(x) = P_1 x^n + P_2 x^{n-1} + \ldots + P_n x + P_n$$

Equation 2-3: Polynomial coefficients equation

The SNR was calculated. The signal for this purpose is considered the motor imagery EEG signal, while the noise (mental noise) is considered the EEG signal not performing motor imagery.

To compute the SNR, a peak value between –1sec and +1sec around the stimulus was obtained, being the signal value. Then, to obtain a noise value we compute the root mean square (RMS) of the EEG signal between 0.3sec and 0.4sec after the peak value. This time range was chosen because from the results in cross correlation, we know that 0.3sec after the peak value of motor imagery the signal is goes back to its previous stage.

The RMS was selected because is a statistical measurement used when the magnitudes of the signals vary in quantity and the mental noise in this case presents such characteristics, see Equation 2-4 *(39)*.

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} xi^2}{n}}$$

Equation 2-4: Root mean square formula

The actual SNR values were obtained by dividing the peak value between the RMS of the relaxing EEG signal. The SNR results presented many outliers making it difficult to draw conclusions. Therefore it was filtered by replacing the outliers with the mean value of a window-size of 25 trials. Then the mean value was recomputed for each session.

Further analysis was computed to the correlation coefficients and reaction times. These analyses are:

- Mean value of correlation coefficients and reaction times per session
- Standard deviation of correlation coefficients and reaction times per session
- Histogram of reaction times

CHAPTER 3: RESULTS AND ANALYSIS

Reaction time

The reaction time results are shown in appendix 1 and Table 3-1 reports the mean reaction time, the mean end point (which is the latest reaction time on each group), and the standard deviation of each group.

Table 3-1: Reaction time results

Stimulus direction	EEG channel	Distribution	Mean (sec)	End point (sec)	Standard Deviation (sec)
Subject 1					
Right	Centre	Gaussian	0.55	1.5	0.27
Right	Left	Skewed Gaussian	0.47	1.2	0.3
Right	Right	Skewed Gaussian	0.45	1.1	0.26
Left	Centre	Gaussian	0.64	1.5	0.28
Left	Left	Gaussian	0.70	1.5	0.3
Left	Right	Gaussian	0.67	1.5	0.3
Mean total results			0.581	1.383	0.289
Subject 2					
Right	Centre	Skewed Gaussian	0.53	1.4	0.32
Right	Left	Gaussian	0.47	1.5	0.26
Right	Right	Skewed Gaussian	0.54	1.5	0.33
Left	Centre	Gaussian	0.50	1.5	0.26
Left	Left	Skewed Gaussian	0.40	1.2	0.29
Left	Right	Gaussian	0.53	1.5	0.27
Mean total results			0.500	1.433	0.292

Stimulus direction	EEG channel	Distribution	Mean (sec)	End point (sec)	Standard Deviation (sec)
Subject 3					
Right	Centre	Gaussian	0.53	1.5	0.31
Right	Left	Gaussian	0.68	1.3	0.28
Right	Right	Gaussian	0.49	1.1	0.23
Left	Centre	Skewed Gaussian	0.66	1.45	0.36
Left	Left	Linear decrease	0.44	1.5	0.31
Left	Right	Gaussian	0.62	1.3	0.30
Mean total results			0.575	1.35	0.305
Subject 4					
Right	Centre	Gaussian	0.57	1.4	0.26
Right	Left	Skewed Gaussian	0.51	1.4	0.35
Right	Right	Gaussian	0.68	1.5	0.28
Left	Centre	Gaussian	0.56	1.2	0.30
Left	Left	Gaussian	0.83	1.5	0.35
Left	Right	Gaussian	0.53	1.5	0.30
Mean total results			0.618	1.41	0.313
Subject 5					
Right	Centre	Gaussian	0.73	1.5	0.33
Right	Left	Gaussian	0.78	1.5	0.30
Right	Right	Gaussian	0.69	1.5	0.32
Left	Centre	Gaussian	0.61	1.5	0.35
Left	Left	Skewed Gaussian	0.67	1.5	0.40
Left	Right	Skewed Gaussian	0.61	1.5	0.39
Mean total results			0.685	1.5	0.354
General results			**0.592**	**1.418**	**0.311**

Table 3-2 presents the reaction time polynomial fitting functions from the least square mean fit.

Table 3-2: Reaction time polynomial functions

Measurement: Reaction time

Subject: 1		
Direction	Channel	Polynomial function
Right	1	$P1(x) = 0.0018x + 0.4467$
Right	2	$P2(x) = 0.0025x + 0.2857$
Right	3	$P3(x) = 0.0004x + 0.4151$
Left	1	$P4(x) = 0.0003x + 0.5691$
Left	2	$P5(x) = - 0.0001x + 0.6895$
Left	3	$P6(x) = 0.0003x + 0.6288$

Subject: 2		
Direction	Channel	Polynomial function
Right	1	$P1(x) = - 0.0008x + 0.5611$
Right	2	$P2(x) = 0.0010x + 0.3600$
Right	3	$P3(x) = 0.0005x + 0.5252$
Left	1	$P4(x) = 0.0004x + 0.4803$
Left	2	$P5(x) = - 0.0010x + 0.4531$
Left	3	$P6(x) = 0.0008x + 0.4875$

Subject: 3		
Direction	Channel	Polynomial function
Right	1	$P1(x) = - 0.0003x + 0.5355$
Right	2	$P2(x) = 0.0015x + 0.6025$
Right	3	$P3(x) = 0.0012x + 0.4409$
Left	1	$P4(x) = - 0.0015x + 0.7293$
Left	2	$P5(x) = 0.0011x + 0.4067$
Left	3	$P6(x) = - 0.0021x + 0.7618$

Subject: 4		
Direction	Channel	Polynomial function
Right	1	$P1(x) = 0.0004x + 0.5105$
Right	2	$P2(x)= - 0.0001x + 0.5072$
Right	3	$P3(x) = - 0.0001x + 0.6470$
Left	1	$P4(x) = - 0.0004x + 0.60$
Left	2	$P5(x) = -0.0004x + 0.8098$
Left	3	$P6(x) = 0.0005x + 0.4510$

Measurement: Reaction time

Subject: 5		
Direction	Channel	Polynomial function
Right	1	$P1(x) = 0.0010x + 0.6025$
Right	2	$P2(x) = -0.0010x + 0.8501$
Right	3	$P3(x) = 0.0001x + 0.6348$
Left	1	$P4(x) = 0.5607$
Left	2	$P5(x) = 0.0010x + 0.6121$
Left	3	$P6(x) = 0.0008x + 0.5033$

Analysis of reaction time

From Table 3-1 observe that all reaction times are between 0 and 1.5sec. Taking into account all subjects, the mean reaction time is 0.592sec, which is the most important result in this study. It shows consistency with other studies that have done similar experiments but have used other methods to process the data, such as frequency domain analysis *(25, 26)*.

The mean end point of the reaction times is 1.418sec, and the mean standard deviation is 0.311sec. 68.2% of the reaction times are between 0.281sec and 0.903sec.

From the functions in

Table 3-2 above, we can see that the offset constants are between 0.28sec and 0.80sec, and the slopes are between 0 and 0.0025 sec/trials. This slope values are small enough to determine that the reaction time remains almost constant. More analysis in this matter is done next with the histograms.

Graphs in appendix 2 show the histograms of the reaction time. 20 out of 30 graphs (representing 66.66%) have a Gaussian distribution, 9 have a skewed

Gaussian distribution (representing 30%), where the values remain almost constant until a falling value where it drops, and 1 decreases linearly form 0 to 1.5 sec. Next, a list of the skewed Gaussian graphs with the dropping values:

1) Subject 1, right stimulus, left channel, dropping value 1.2sec.
2) Subject 1, right stimulus, right channel, dropping value 1.1sec.
3) Subject 2, right stimulus, centre channel, dropping value 0.8sec.
4) Subject 2, right stimulus, right channel, dropping value 1.2sec.
5) Subject 2, left stimulus, left channel, dropping value 0.7sec.
6) Subject 3, left stimulus, centre channel, dropping value 1.2sec.
7) Subject 4, right stimulus, left channel, dropping value 0.75sec.
8) Subject 5, right stimulus, left channel, dropping value 1sec.
9) Subject 5, right stimulus, right channel, dropping value 0.6sec.

The 30% of results that present a skewed Gaussian possibly have a Gaussian distribution but the motor imagery is small and it is embedded in noise. The one graph that has a linear decrease might also present a great amount of noise, because that same subject in all the other combinations of directions and channels presents Gaussian distributions.

Comparing the reaction times between subjects, we can see that some of them are faster than others by approximately 0.2sec. 33.33% of the mean reaction times are between 0.5sec and 0.6sec, 33.33% are between 0.6sec and

0.7sec, 20% are between 0.4sec and 0.5sec, and only 3.33% are 0.8sec or higher.

Subjects 1 and 5, who present improvements of the EEG signal according to the correlation coefficients discussed later, are the subjects whose mean reaction times are higher than the rest of the participants, 0.581sec and 0.611sec respectively. In between this two, subject 4 obtained a 0.61sec mean reaction time, but since the correlation data does not give conclusive results, it is not clear if these reaction times are really from the motor imagery exercises.

Subject 3 has a mean reaction time of 0.575sec, and the correlation coefficients of this subject were very consistent. Subject 2, has the lowest mean reaction time, 0.50sec and there were no significant results from her correlation coefficients.

Difference in reaction time between right and left

Table 3-3: Difference in reaction time between right and left

Subject	Mean reaction time to Left direction (sec)	Mean reaction time to Right direction (sec)	Difference between left and right means (sec)	Strong hand
1	0.669	0.493	0.176	Right handed
2	0.483	0.516	-0.032	Left handed
3	0.576	0.573	0.003	Right handed
4	0.645	0.592	0.053	Right handed
5	0.6351	0.736	0.101	Right handed

The table above demonstrates that 4 subjects reacted faster with their dominant side, except for subject 5. Even though Table 3-3 shows a difference from 0.003sec to 0.1sec on the mean values from right to left, comparing this rage with the total reaction time range and reviewing the all the reaction time values in appendix 1, we can determine that there is no significant difference in reaction time between the right and left motor imagery.

Difference in reaction time among channels

Results do not suggest any difference among the reaction time comparing the 3 channels. Table 3-1, which shows the mean reaction time, demonstrates that there is no faster or slower channel in any subject. This can also be compared in the appendix 1.

Standard deviation on reaction time

The standard deviation per session results (see appendix 4) reports no significant change over the repetition of the motor imagery in general. Subject 1 reported over the last 50 trials a smaller standard deviation in 4 channels. Subject 4 presented a smaller standard deviation in 3 graphs over the last 100 trials, and subject 5 in 2 graphs also over the last 100 trials. This suggests that with more repetitions over 1000 there is the possibility that the response time standard deviation varies less and therefore the reaction time would be more precise.

Correlation coefficients

The results of correlation coefficients can be observed in appendix 5 and the polynomial functions from the least square mean in Table 3-4.

For the correlation coefficients each subject will be reported separately, because their results invite for different analyses. Also a future work section is included along with the subject's comments.

Table 3-4: Correlation coefficients polynomial functions

Measurement: Correlation Coefficients

Subject: 1		
Direction	Channel	Polynomial function
Right	1	$P1(x) = - 0.0001\text{x}10^{6} x^{2} + 0.0167 \text{x}10^{6} x + 2.7375 \text{x}10^{6}$
Right	2	$P2(x) = 0.0069 \text{x}10^{6} x + 1.8850 \text{x}10^{6}$
Right	3	$P3(x) = - 0.0054 \text{x}10^{6} x + 2.4738 \text{x}10^{6}$
Left	1	$P4(x) = - 0.0001 \text{x}10^{6} x^{2} + 0.0134 \text{x}10^{6} x + 3.4485 \text{x}10^{6}$
Left	2	$P5(x) = 0.0097 \text{x}10^{6} x + 2.2643 \text{x}10^{6}$
Left	3	$P6(x) =-0.0017 \text{x}10^{6} x + 1.9773 \text{x}10^{6}$

Subject: 2		
Direction	Channel	Polynomial function
Right	1	$P1(x) = 0.0010 \text{x}10^{6} x + 4.3324 \text{x}10^{6}$
Right	2	$P2(x) = - 0.0003 \text{x}10^{6} x^{2} + 0.0498 \text{x}10^{6} x + 6.4513 \text{x}10^{6}$
Right	3	$P3(x) = 0.0066 \text{x}10^{6} x + 4.6153 \text{x}10^{6}$
Left	1	$P4(x) = 0.0075 \text{x}10^{6} x + 3.6804 \text{x}10^{6}$
Left	2	$P5(x) = - 0.0004 \text{x}10^{6} x^{2} + 0.0699 \text{x}10^{6} x + 5.9622 \text{x}10^{6}$
Left	3	$P6(x) = 0.0086 \text{x}106\ x + 4.6113 \text{x}106$

Subject: 3		
Direction	Channel	Polynomial function
Right	1	$P1(x) = 0.0046 \text{x}10^{6} x + 2.7414 \text{x}10^{6}$
Right	2	$P2(x) = 0.0002 \text{x}10^{6} x + 6.6849 \text{x}10^{6}$
Right	3	$P3(x) = 0.0008 \text{x}10^{6} x + 4.5869 \text{x}10^{6}$
Left	1	$P4(x) = 0.0082 \text{x}10^{6} x + 2.0430 \text{x}10^{6}$
Left	2	$P5(x) = - 0.0034 \text{x}10^{6} x + 3.5680 \text{x}10^{6}$
Left	3	$P6(x) = 0.0087 \text{x}10^{6} x + 1.9131 \text{x}10^{6}$

Measurement: Correlation Coefficients

Subject: 4		
Direction	Channel	Polynomial function
Right	1	$P1(x) = 0.0001\ x10^6\ x^2 - 0.0105\ x10^6\ x + 2.8937\ x10^6$
Right	2	$P2(x) = -0.0029\ x10^6\ x + 2.6903\ x10^6$
Right	3	$P3(x) = -\ 0.0083\ x10^6\ x + 6.2359\ x10^6$
Left	1	$P4(x) = 0.0044\ x10^6\ x + 1.1551\ x10^6$
Left	2	$P5(x) = 0.0174\ x10^6\ x + 9.1277\ x10^6$
Left	3	$P6(x) = -\ 0.0020\ x10^6\ x + 2.8019\ x10^6$

Subject: 5		
Direction	Channel	Polynomial function
Right	1	$P1(x) = -\ 0.0002\ x10^6\ x^2 + 0.0392\ x10^6\ x + 3.8482\ x10^6$
Right	2	$P2(x) = -\ 0.0001\ x10^6\ x^2 + 0.0265\ x10^6\ x + 4.1830\ x10^6$
Right	3	$P3(x) = -\ 0.0001\ x10^6\ x^2 + 0.0175\ x10^6\ x + 3.4301\ x10^6$
Left	1	$P4(x) = -\ 0.0002\ x10^6\ x^2 + 0.0303\ x10^6\ x + 6.5762\ x10^6$
Left	2	$P5(x) = 0.0089\ x10^6\ x + 3.4663\ x10^6$
Left	3	$P6(x) = -\ 0.0001\ x10^6\ x^2 + 0.0133\ x10^6\ x + 3.8398\ x10^6$

Subject 1

Relevant results:

The correlation coefficients from subject 1 showed in 3 out of 6 graphs increments in values, see Table 3-5. The linear slope is more pronounced in the last 100 trials. Refer to appendix 5.

In the results from the right direction channels 1 (centre) and 3 (right hemisphere), and left direction channel 1 (centre), outliers are present in the first 50 trials that have a standard deviation of $2.5x10^6\mu V$.

Table 3-5: Subject 1, cross correlation slope values

Direction	Channel	Slope (μV/trial)
Right	1	0.000401
Left	1	0.000401
Left	2	0.0002

Meaning of results:

The increase in values demonstrate that the EEG signal slowly changed over repetition of motor imagery, suggesting that the brain is being trained and the EEG signal is becoming more consistent over the repetitions. The outliers in the beginning give away that the subject was uncertain of the mental activity to perform or felt uncomfortable, anxious, or some other unpleasant feeling.

Future experimentation:

Further repetition of motor imagery would confirm change in the EEG signal, since the slope values are small. There is a possibility that the data is accommodating in long waves, but 500 trials do not give enough evidence to make a strong conclusion.

At the same time, subject 1 should be tested in a BCI with real-time feedback. Feedback will help the subject to focus and produce a more reliable EEG signal. With feedback the participant will be able to know immediately the effect of the preformed motor imagery and can experiment different motor imageries, such as thinking of moving the hands up and down, or sideways. Then the subject can decide which motor imagery has a better impact on the feedback output.

Subject 1 starting comment:

My approach to motor-imagery with my hands is to decide to move a particular hand following the arrow and immediately suppress the motion. So it is more physical than pure imagination. I feel it like making a motion without motion.

Subject 1 ending comment:

I find it difficult to modify (improve) my approach to any activity without an immediate feedback. Because our brain-training experiment was such a case, I tried different ways of focusing on the task at hand in different sessions. In some cases my motor-imagery was based on abstracting imagination from real motion and in other cases it was more physical with starting the motion and suppressing it immediately. The second approach was easier for me and thus I suspect the results were better. The amount of sleep I had before the experiment in all sessions definitely had a strong effect on my ability to concentrate and force my brain to perform the expected task.

Subject 2

Relevant results:

The results form subject 2 are scattered (see appendix 5). They show no pattern, no sequence and no consistency. In comparison to all the subjects in this study, subject 2 has the most scattered data-points, with a standard deviation changing from $1\text{x}10^6\mu V$ to $16\text{ x}10^6\mu V$, whereas the range among the other participants was from $0.5\text{x}10^6\mu V$ to $6\text{ x}10^6\mu V$.

Meaning of results:

Results suggest that subject 2 was never able to concentrate while performing motor imagery mental exercise. It proposes an active brain that is thinking of many things at the same time. The signal from the motor imagery is hidden in among this brain signal noise, since the output of these other thoughts had bigger amplitudes in the EEG signal.

Further experiments:

It would be interesting to have subject 2 trained in meditation for a period of time, e.g. a year, and then repeat the motor imagery experiment. Meditation has been proven to help regulate EEG signals *(28)*, more information about this topic is discussed in Chapter 4.

The organization of the ideas and thoughts might go through a process while practicing meditation and the possibility of having more consistent results exists. At the same time, the option that some people might never be able to have a useful EEG signal for the purpose of controlling a BCI also exists.

Subject 2 starting comment:

The experiment is very interesting and I am fascinated to watch my own mind at work. I admire people who can focus completely but I wander a bit – ok, a lot-. I get curious about people who meditate. Does this make a difference? I find myself trying to predict which way the arrow will point next. I guess I'm looking for patterns but being inside the experiment means I am too involved remembering which hand is left and which is right to actually find the patterns.

Subject 2 ending comment:

I was thinking about which earrings I would buy from the craftsman at the Fair today and how outrageous life is for people like Poolan Devi. This abuse has to stop. I thought about squeezing the muscles in my hand, which was fun because it is not something one thinks about, and thinking about it without doing it made my brain wriggle. I got caught up in the rhythm of the blank, plus sign, and arrow pattern. It is restful. I tried to listen to the silence and most of all I tried not to scratch my eyebrow, which began to jingle half way through.

Subject 3

Relevant results:

The results from subject 3 show consistency in 5 out of 6 data results, the exception being channel 2 (left hemisphere) in the right direction. The correlation coefficients remain constant throughout the study, with an approximate value of $0.35 \times 10^6 \mu V$. There is no increase in the correlation values. Alternatively, the data combining right stimulus obtained in the left side of the brain is scattered, with a variation in the standard deviation form $0.33 \times 10^6 \mu$ to $14 \times 10^6 \mu$.

Meaning of results:

Results in subject 3 show no improvement or change in the signals, therefore no training occurred. Nevertheless, the consistency in the results suggests no training is needed since the signal is so steady, which means the reliability on this signal is high. Subject 3's EEG signal can be used as a command signal. There is no obvious explanation for the scattered data points.

Future experimentation:

One approach is to do more motor imagery repetitions on subject 3 to confirm the consistency of the data. The second approach is to use a BCI with real time feedback to confirm the usefulness of the EEG signal.

Subject 3 starting comment:

My personality: Even though I am a party machine who likes to drink on the weekends I study like an academic. I drink hard and study hard.

My experience on the machine: while the test is running I try to concentrate on the screen but sometimes my mind wonders of other things including homework, breasts, essays, breasts, lunch, breasts and my weekend which has hopefully included something to do with breasts. When I catch myself doing this I quickly get back into focus. When the arrow points I picture my arm taking one large grab at the air beside me. Sometimes the grabs are not as strong as others. Near the end of the second test I get relaxed and a little sleepy so I do not think that my grabs are as strong as the when I begin the test.

Subject 3 ending comment:

During the first few sessions I would picture my hand taking quick, multiple grabs when the arrow pointed to the left or right. I believe I would be about three grabs. Then I changed and pictured myself taking one large grab, which I continued to do for the remaining sessions. After the first two weeks I would find my mind wondering a little but I would still picture my hand taking large grabs. My lack of focus would make my concentration not as strong. During the last few sessions I made sure to try my hardest to focus on the screen.

I can multitask but have a short attention span. I cannot focus on one thing for to long or I find my mind wondering. It happens whether I am at work, studying or doing homework. However, I prefer not to multitask. I would prefer to focus on one thing and then do the other but if I have to, I have no problem doing multiple tasks at a time.

Subject 4

Relevant results:

Subject 4 has different results depending on the direction of the visual stimulus. The results from the motor imagery of the left hand (direction 2) are consistent. There are no increments in the correlation coefficients and the standard deviation ranges form $0.5 x 10^6 \mu V$ to $2 x 10^6 \mu V$. This is the smallest standard deviation variation computed in this study.

Data from the right motor imagery (direction 1) in channels 1 (centre) and 2 (left hemisphere) is mainly consistent but presents outliers all along the 500 trials. The standard deviation ranges from $1 x 10^6 \mu V$ to over $8 x 10^6 \mu V$. The results from the right direction in channel 3 (right hemisphere) is scattered.

Meaning of results:

The EEG signal coming from motor imagery on the left side is reliable and can be used as a control signal for a BCI. Unlike the EEG signal from the motor imagery of the right side, which cannot be use for control. This last signal does not show any improvement of training through the study.

Future experimentation:

A similar study with a different motor imagery exercise could be tested on subject 4 to review if his results show the same difference when differing form one side to the other.

Subject 4 starting and ending comments:

The subject did not document the experience.

Subject 5

Relevant results:

All the correlation coefficients from subject 5 increase consistently, almost linearly. Two graphs have a linear slope value of approximately 0.001202, other two graphs present a value of 0.000802, and the resting two have a linear slope value of 0.000601, refer to Table 3-6. The highest linear slope value in subject 5 is double the highest slope value from subject 3 and it is eight times bigger than the highest value from subject 1.

Table 3-6: Subject 5, cross correlation slope values

Direction	Channel	Gradient (μV/trial)
Right	1	0.001202
Right	2	0.001303
Right	3	0.000802
Left	1	0.000802
Left	2	0.000601
Left	3	0.000601

The EEG signal acquired in the middle of the head (channel 1) has a standard deviation range greater than the standard deviation range from the other two channels.

- Standard deviation range from channel 1: $0.1 \times 10^6 \mu V$ to $0.5 \times 10^6 \mu V$
- Standard deviation range from channel 2 and 3: $0.1 \times 10^6 \mu V$ to $0.3 \times 10^6 \mu V$

The EEG signal on subject 5 was clear and clean. The participant showed a strong EEG signal response to the visual stimulus since the first session, but his signal improved in clarity and cleanness as the repetitions happened.

The unprocessed EEG signal on subject 5 has a different pattern in comparison to the rest of the participants. Between the stimuli, the EEG signal has greater amplitude and lower frequency (4 and 5 Hz) than while performing motor imagery. Illustrations of the EEG signal from session 1 and 20 are presented in appendix 9, where a visual comparison of the signals can be done.

Meaning of results:

Results from subject 5 during the training processed suggest that the participant learned to relax the brain and very probably clear the mind from distracting thoughts.

On the other hand, slope values in the results from correlation coefficients present a clear change on the motor imagery signal as repetitions happened. The EEG signal at the end of the experiment can be used as a controlling signal for a BCI application, with the confidence that it is repeatable and reliable.

This subject had a bold head in all the sessions; this minimizes noises that come from poor electrode placement. This might have affected in a positive manner the results.

Future experimentation:

Subject 5 should be tested in a BCI where the signal processing has an adaptive algorithm *(29)*, since the EEG signals changes with the repetitions. As a BCI user, confirmation of the mental motor imagery signal strength can be proven.

Subject 5 starting comment:

Initially, concentrating on the symbols was challenging and I put in a lot of effort to ensure that I did not break my concentration. With my more recent tests, concentrating on the symbols was rather effortless.

I generally find that I am a fast learner, and I have little difficulties concentrating for long periods.

I have a certain approach to everything I do, which is to first understand the concept of what I'm doing, and then focus on the finer details. This approach was developed after experiencing failure and striking to understand what the best approach was to solving problems.

Also, I generally try not to consciously remember details unless it's necessary and focus on storing concepts in my mind.

Subject 5 ending comment:

I initially exerted considerable effort in concentrating on the symbols presented. After the second session, I found the task of concentrating on the symbols to be rather effortless.

On several occasions, I attended the sessions in a sleep-deprived state, and found that I had to once again exert considerable effort in concentrating. During one of these sessions, I had to take three tests, instead of the usual two, and found this to be mentally exhausting.

In order to understand my brain signals, it would be insightful to know a bit about my personality. I have generally observed that I think and approach situations differently from other people, but this has not always been the case. Several events occurred in my life that caused me to re-evaluate my perspective and modify my mind.

Without getting into the psychological details (as I have no background in this area), modifying your mind necessitates you achieving a high degree of control of it. The key factors, which I found to be beneficial in achieving this purpose, are your preconceptions, ability to conceptualise, memory, consciousness and health.

I work better on my own, and prefer to tackle tasks serially, i.e., I dislike excessive multitasking. I am risk adverse and generally base everything I do on a logical decision. Also, I have observed that I struggle with certain tasks that most people easily adapt to, such as driving. I initially found driving to be an overwhelming experience, but mastered it based on a learned behaviour, as opposed to a natural progression.

Signal to noise ratio

The results form SNR are presented in appendix 8. In subject 1, 2 and 5 the mean SNR is 3, while in subjects 3 and 4 the SNR is 3.4. In all subjects SNR does not present any difference in the right and left motor imagery nor in the two brain hemispheres.

These results prove that the motor imagery signal is approximately 3 times greater than the EEG signal that follows the mental exercise. This indicates that motor imagery signal has the potential to be converted into a BCI command. On the other hand, the results in this study are not strong enough to have significant conclusions.

Further work will have to be done to improve this parameter. Is it very possible that the SNR will give more successful results if analysed in the frequency domain.

Noises and errors

Finding the noises and the errors in research is important because they help understand the data better and consider improvements for the future. In this document, noises and artifacts are considered signals that are part of the output but are not the target signal of the study and an error to be a mistake that occurs during any part of the process. Unfortunately, not all noises and/or errors are measurable; therefore, the only possible thing to do is to try and minimize them.

Noises

The external noises are mainly utility frequency of 60Hz and stray noise emitted by devices in the laboratory area. To overcome this problem the data was acquired inside a shielded room. A notch filter of 60Hz and a low pass of 30 Hz also helped minimize the noise in the signal. Proper electrode grounding on the subjects' ears minimized body noise.

Artifacts

Biological artifacts are commonly defined as non-cerebral signals that contaminate the EEG measured signal. The main ones are eye artifacts, such as blinking and eye movement. For the purpose of this study an incorrect mental state is considered an artifact.

Asking subjects to blink in the relaxing stage when the screen was blank minimized blinking artifacts. Eye movement is usually considered an artifact while using EEG, and to compensate for it, electromyography is acquired around the eyes. In this study eye-movement was not a concern.

Mental artifacts are considered in this study mental thoughts that are not related to the study's motor imagery exercise. Some examples of mental artifacts are, lack of concentration, thinking of other things while doing the experiment, and having no interest in the experiment. Mental artifacts are reported in the participants' comments. The mental status artifact encompasses the subject's experiences of state of alarm, fatigue, frustration, confusion, etc. while participating, because these feelings will affect the EEG signal related to the visual stimulus.

To minimize these situations we presented a questionnaire in the beginning of the study to assure the participants were interested and comfortable with the study and between sessions they were asked if they felt comfortable and peaceful. Nevertheless, the possibility of a subject not reporting true mental state exists.

Another type of noise is external artifact, which includes motion by the subject, which was minimized by sitting the subjects in a conformable chair with armrests and making sure they were comfortable before starting the data acquisition.

Poor placement of electrodes is also an external artifact. To decrease it, one researcher was in charge of electrode placement, keeping consistency in the amount of conductive paste, in moving hair to place the electrodes, and in measuring the heads before placing the electrodes. Because placing the electrodes in the exact location every session is virtually impossible, as we had 10 acquisition days over a period of 2 months, electrode placement is also considered an error, with minimal significance.

Errors

Subjects' erroneous responses to the visual stimulus are errors in the data. If the subject did not do a mental exercise while the stimulus was presented is considered an error. Also, if the subject thought of moving the wrong hand is considered an error. In this study there was no compensation of these types of errors.

Other researchers have been and are still working on a signal processing method that compensates these types of errors, mainly in automated processes that find motor imagery signal *(14, 17, 30)*.

CHAPTER 4: DISCUSSION

Reaction time discussion

Reaction time was consistent and reliable throughout the study in all participants. For a motor imagery based BCI, there is certainty that no response will happen after 1.5sec and that over half of the responses will occur between 0.5sec and 0.7sec. A study done at the Tokyo Institute of Technology, confirms these results *(26)*. This last article presents a very similar study, with signal analysis in frequency domain. Their results shows that the vision task happens at 0.3sec to 0.4sec after the stimulus and that the high potential of the EEG signal is between 0.5sec and 1sec, which is the same reaction time that this study obtained.

Because reaction time is consistent we can conclude that motor imagery does not become automated after 1000 repetitions, therefore, the signal will be present and measurable on the motor cortex area in the scalp consistently. We can also conclude that motor imagery is a reliable signal for controlling a BCI since we know with certainty that it will happen within a certain range of time.

Correlation coefficients discussion

From the correlation results there were 2 objectives: 1) to determine EEG signal changes, and 2) to evaluate the difference between right and left motor imagery. Next, the discussion of these two topics separately is presented.

EEG changing signal

Reviewing the results of how the EEG signal changes over time, 3 groups of subjects are formed. The first group includes subjects that showed training, the second group includes subjects that did not show training but their signal is still or could be useful for the BCI application, and third one includes subjects that have no pattern or order in the data.

Extrapolating these 3 groups to the general population, we can say that there are some people that will be able to train their EEG signal and will reproduce a repeatable, consistent, and reliable signal for the use of BCI after brain training over motor imagery repetition. From this trained group, the number of repetitions and the time they will take to achieve a clean signal varies on each individual and there is no scientific rule for this matter.

An article published in 2002, written by researchers from the Royal Hospital fro Neuro-disability, London in conjunction with the University of Keel, Staffordshire, present the different mental states and approaches to motor imagery *(23)*. This article in addition to the subjects comments, demonstrate this group of people in general have a very organized mind, their thoughts are clear, they tend to be more analytical, they can focus easily and remain focused for extended periods of time, and they are not good multi-taskers. For this group of people, the BCI would be recommended to have an adaptive method of processing, giving a mutual learning process.

The second group is harder to define but it is very likely that most people fall into this category. They are people that might be able to train their brain, but it will not be as easy as the members from the first group. This group would take longer to train the brain and some of them might not be able to achieve this goal. At the same time, members of this group like subject 3 are potentially ideal candidates for BCI interface users because their signal is so repeatable without the necessity of a formal training. The personality of this group would encompass people that are not extremists, neither in order nor in disorder, for example.

The third group encompasses certain people that are not able to concentrate their thoughts to only one thing at a time, usually very creative people that are interested in arts. Since these people are having several ideas at once, the EEG signal is not clean, clear, or repeatable; therefore, using motor imagery as a command signal for a BCI or for any other application is not possible. Nevertheless, there is the possibility that with more serious training such as meditation or daily mental exercises with feedback, the EEG signal pattern could improve.

Difference between right and left

From this study we can conclude that the right and left motor imagery produce the same results. However, some papers have different results and conclusions in this matter *(15, 25, 31)*.

Numerous reasons could explain the diversion of results. First, the EEG system resolution difference, with greater resolution, more data points is acquired and therefore, there is possibly more information in the signal. Second, with regards to signal processing and signal analysis, most papers that report information on BCI are analysing the data in frequency domain or other procedures that differ from the ones used in this study. In this study we selected a time domain analysis because we believed, at that moment, that this type of analysis had been under-evaluated and the possibility of new findings was greater.

Thirdly and most importantly, other experiments include real-time feedback, which is of great value to the participant because they can see in real-time an action related to their present thought, making it easier to the participants to accommodate their thoughts accordingly. In addition, Ishii *et al* and the present study found no significant difference between the right and left signal and as mentioned earlier these studies did not include feedback *(26)*.

Future work

In this section a general future work for the entire study is reported, even though for each subject a suggestion for future work was given. Five main points will be discussed: data acquisition, feedback, signal processing, type of participants, and mediation.

Data acquisition

For the data acquisition there are some modifications that can be done in order to have more beneficial results.

The first modification would be to acquire data from more locations of the cerebral cortex, this means placing more electrodes on the scalp. We would only suggest doing so for few sessions and analyzing the results to review if Cz, C3, and C4 are the optimal electrode placement locations for this study.

The second modification would be to place electrodes around the eye, to record eye-movement while the data is being acquired. The reason for this to ensure that the response signal obtained on from the EEG is not mail coming from eye movement. In order to verify this parameter, there should be a control signal with only eye movements to the sides (right and left). This control signal can be later compared with the raw signal from the experiment and conclusions can be obtained about the relationship between eye-movement and motor imagery.

The third modification would be to change the arrows on the screen that presents the visual stimulus. The arrows used in this study are completely horizontal. This produces greater eye movement than if the arrows where still pointing towards their direction, but instead of being horizontal, they could be slightly facing downwards. The eye movement performed vertically is significantly smaller than in the eye movement performed horizontally.

The last modification would be to change the motor imagery exercise to other types of mental thoughts, with the aim to find difference between the two mental exercises. For example, participants could be asked to perform a mathematical mental exercise or they could be asked to imagine a figure rotating on the space *(41)*. These two types of exercises have been found to give different results on the EEG data.

Feedback

Feedback is the most important feature that should be added to this study. Real-time feedback, as mentioned before will help subjects know the effect on their present thought and will guide them on the mental exercise to perform in order to achieve a certain goal, such as moving a ball to the left or to the right. Having real-time feedback gives participants the opportunity to experiment different ways of thinking the motor imagery thought and immediately knowing which thought has the greatest impact on the output.

Many BCI researchers have this feature and results show the benefits of feedback *(16, 19, 30, 32-34)*.

Real-time feedback has not only been proven to be helpful training the brain but other parts of the human body as well. The study done by Monastra *et al* is based on feedback treatment for people with attention deficit *(35)*; it suggests that real-time biofeedback improves the EEG signal. Also, paper talks about successfully training gait to clinic patients using bio-feedback *(36)*.

The best type of feedback is the one that engages the user in an interesting topic, in a way that the user is not so aware of the brain training. Some researchers are focusing on this topic, by putting games into their BCI output *(20)*.

Signal Processing

The signal processing in this study is stimulus based, knowing the time of when to expect the motor imagery EEG signal. Other studies have an automated pattern recognition signal process *(14, 25, 32, 33, 37)*.

Automated pattern recognition is closer to the actual needs of a BCI. In reality, a BCI is meant to be used free from stimulus restrictions; the ideal situation is that with a specific thoughts the automated process identifies the motor imagery signal and transforms it into a command.

Another possibility in the future is to process and analyse the data in frequency domain. Results from subject 5 clearly present a change in frequency while being relaxed and this change in frequency is clearer as the repetitions increase. Therefore, processing the signal through frequency domain might give even more clear results.

At the same time, other type of compensation signal processing can be added to this study. For example, an enhancement SNR process is documented by Pfurtscheller *(25)*, and an error correction process in automated pattern recognition *(30)*.

Healthy and non-healthy participants

BCI is meant to be use by people that have challenges with their motor abilities, and all subjects in this research as well as in approximately over 90% of the BCI researches around the world study healthy subjects. Few studies report research done on non-healthy participants *(19, 33)*. The main difference is that healthy subjects are used to performing muscle movements, but they are not used to planning muscle movements without performing them. Breaking the habit of movement is more difficult than its seems; participants' corroborate this idea.

This study would be of greater value if the participants had challenges in moving their muscles. Results are expected to be different, since the uncertainty of the mental task is eliminated.

Meditation

Meditation is a mental discipline that has been around for centuries. It can change the mechanism of the brain, allowing it to achieve several levels of awareness among other things *(40)*. Generalizing the different types of meditation there are two main groups: 1) mindfulness meditation and 2) concentrative meditation. These two categories of meditation could be compared to the approaches of BCI training strategies that have been applied up to now.

Mindfulness meditation allows thought and sensations to arise while the attention is kept. Behavioural BCI training strategy is similar, since the subjects are not instructed on how to move the feedback in use. In this case, participants can think anything they want as long as the proper results are delivered.

Concentrative meditation involves focusing on a specific metal activity, such as repeated sound or imagined images. Cognitive BCI training could be compared with this type of meditation, since the subjects focus on a thought with a given stimulus.

Most BCI do not considered mediation as part of their training strategy but in future work meditation could help obtain a more reliable EEG signal, since it has been proven to help stabilize the EEG wave patterns *(28)*. Training the brain could be easier if the participants practiced meditation. This study might obtain a more consistent reaction time and correlation coefficients if subjects practice meditation on regular basis. The subjects would have to start practicing mediation prior to starting the brain training, to obtain the most benefits from it.

A study done at the Psychology Laboratory, at the Russian Academy of Medical Science demonstrates the effect of Sahaja Yoga on the EEG signal *(38)*. It suggested that while practicing meditation some unneeded nervous networks are switched of, increasing the attention level.

Also, a more profound study of the relation between meditation and EEG signals is reported in Cahn *et al*'s paper *(28)*. They report that meditation calms anxiety and confusion, and the signals in the EEG clearly proves such a statement.

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APPENDICES

Indication on how to read the titles of the graphs in the appendixes:

Direction 1 = Right stimulus for the motor imagery

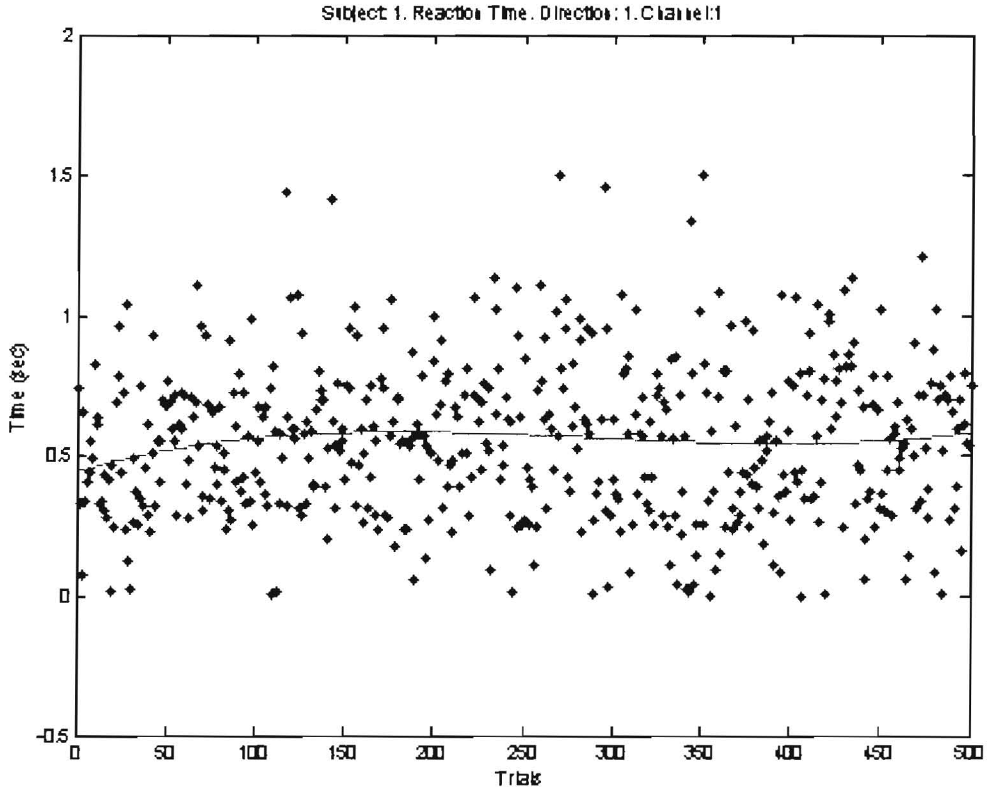
Direction 2 = Left stimulus for the motor imagery

Channel 1 = Centre of the scalp

Channel 2 = Left hemisphere

Channel 3 = Right hemisphere

APPENDIX 1: REACTION TIME RESULTS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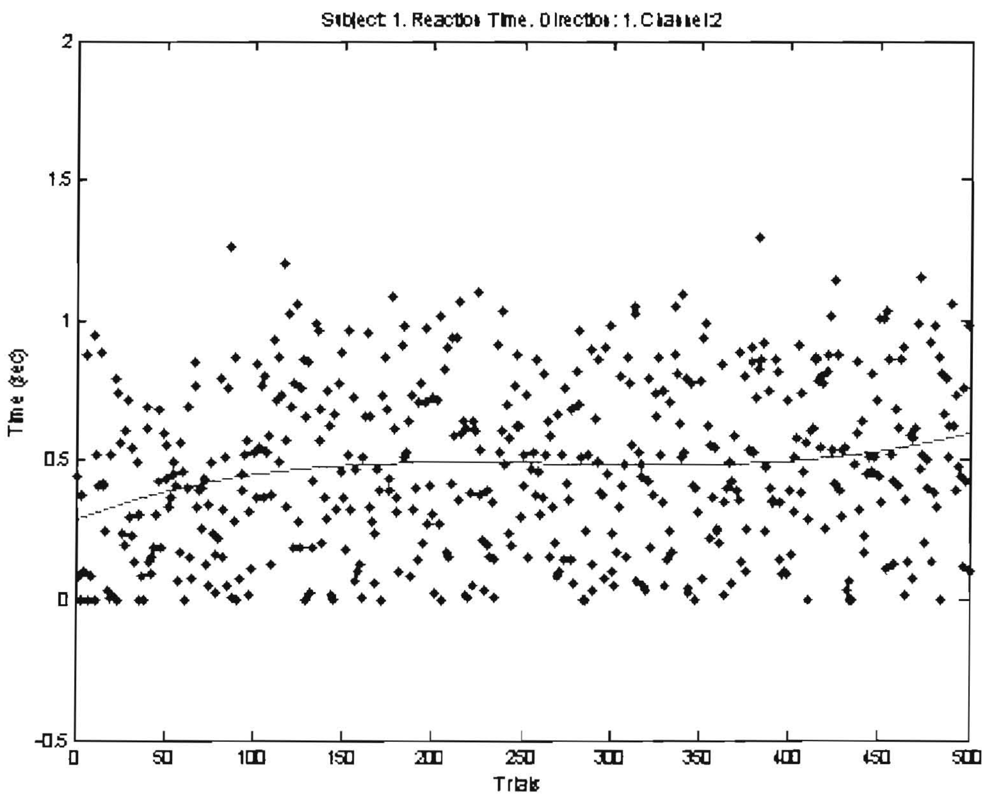
Trials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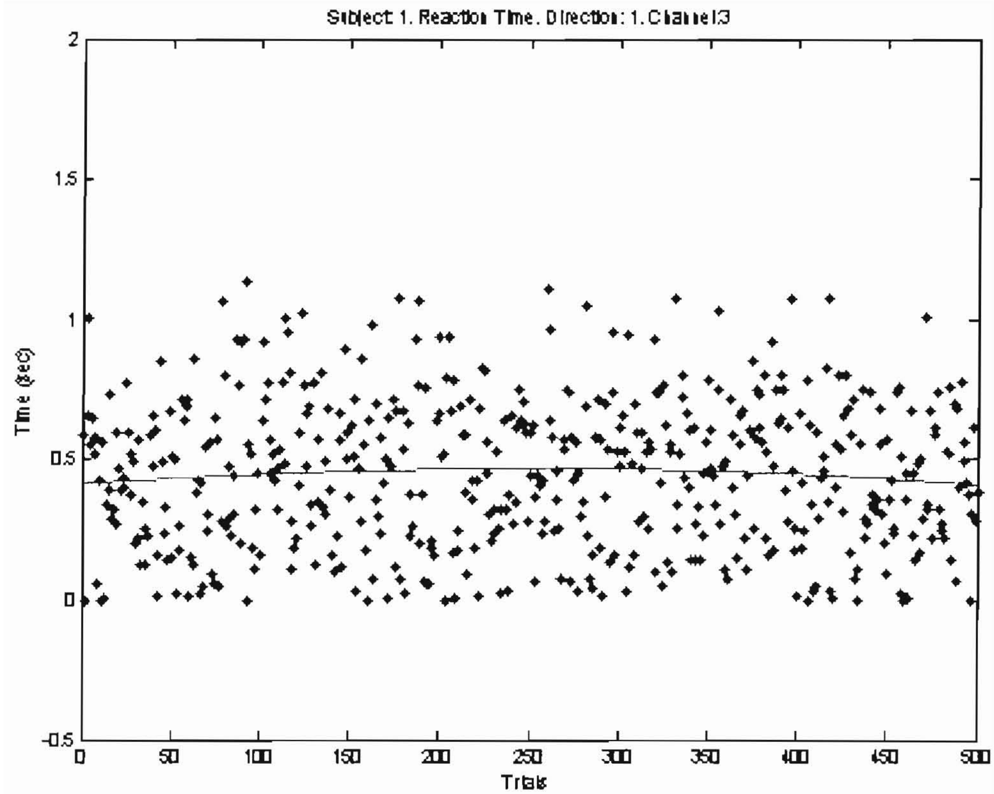
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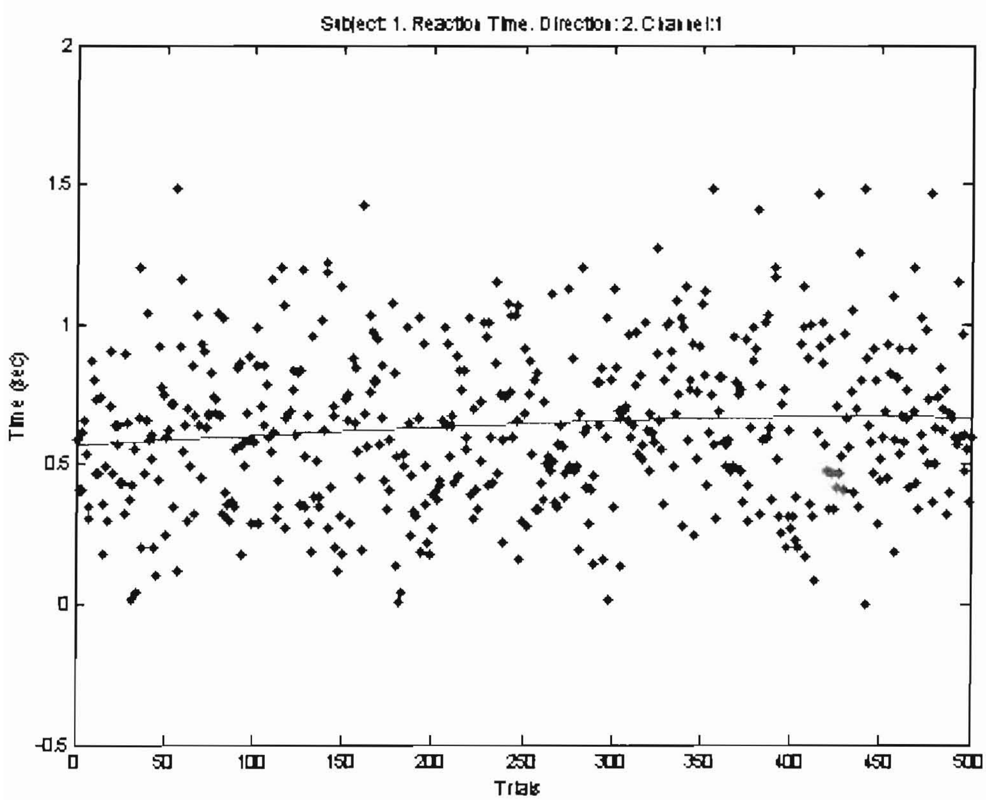
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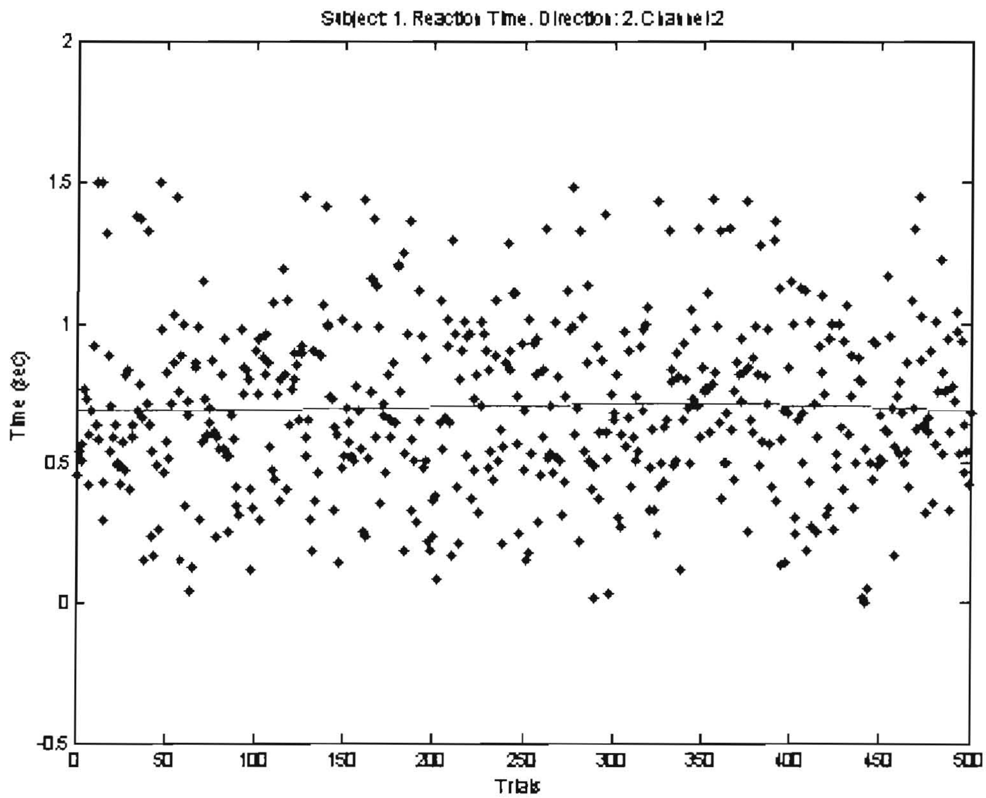
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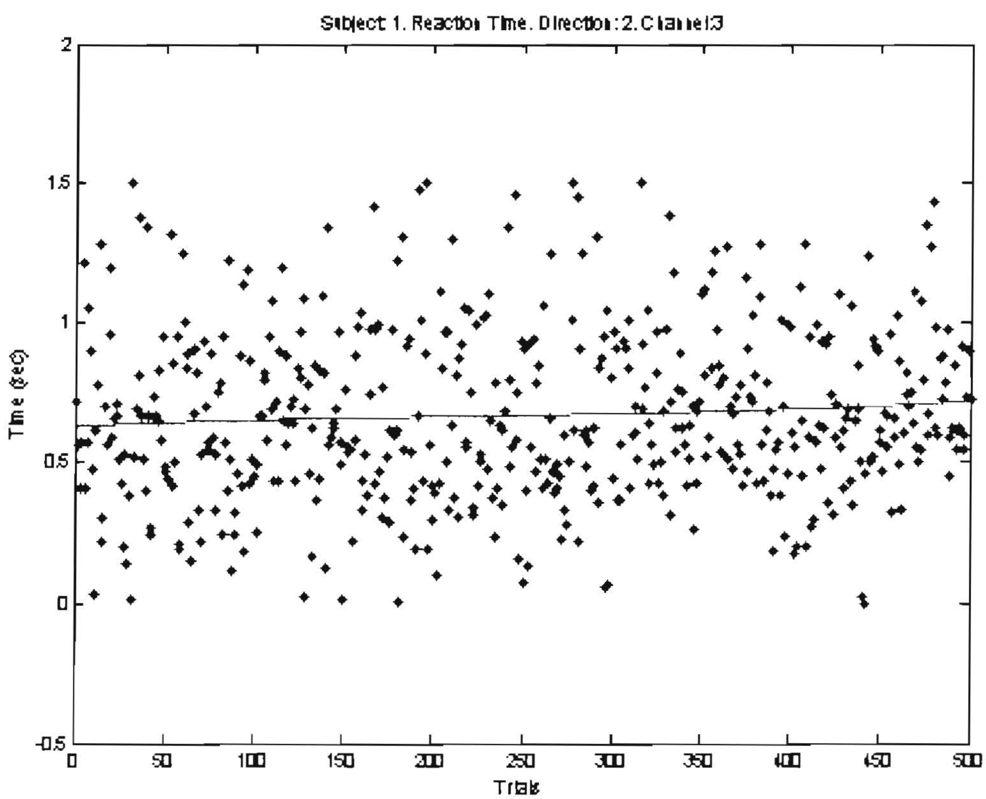
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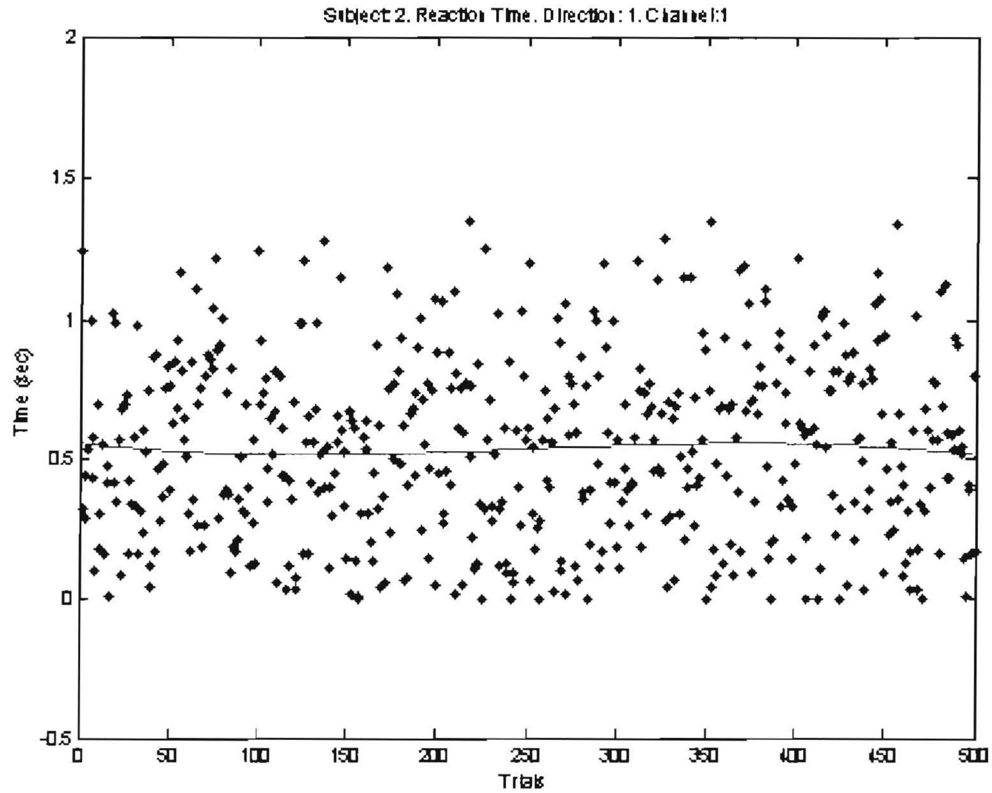
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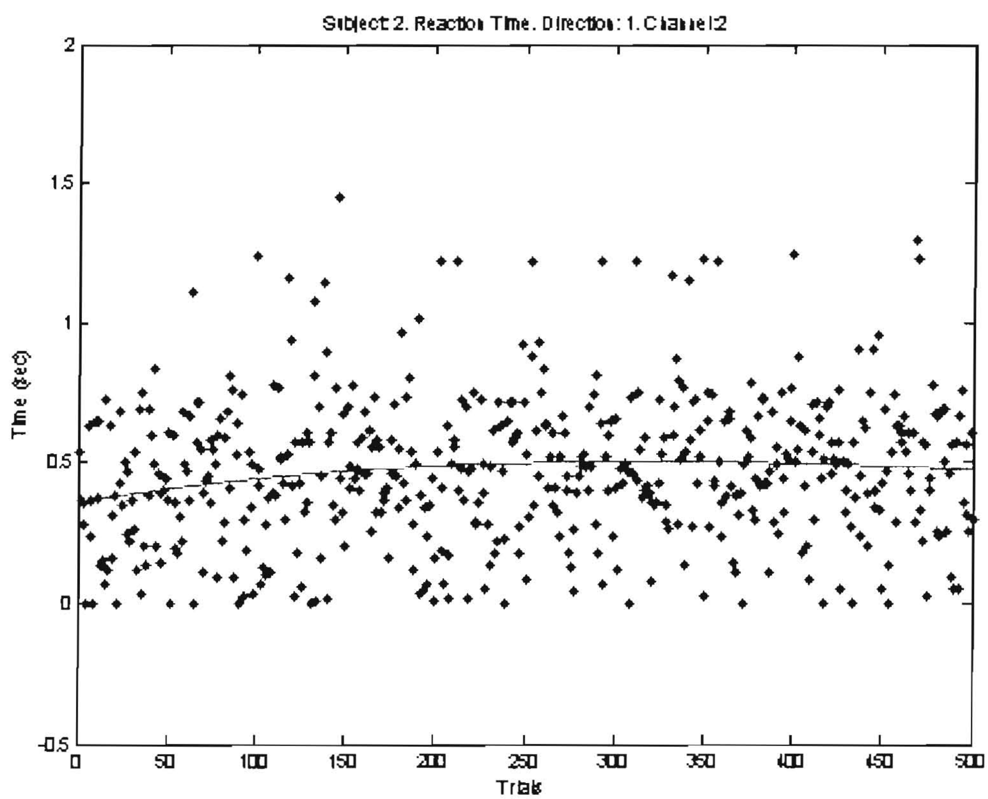
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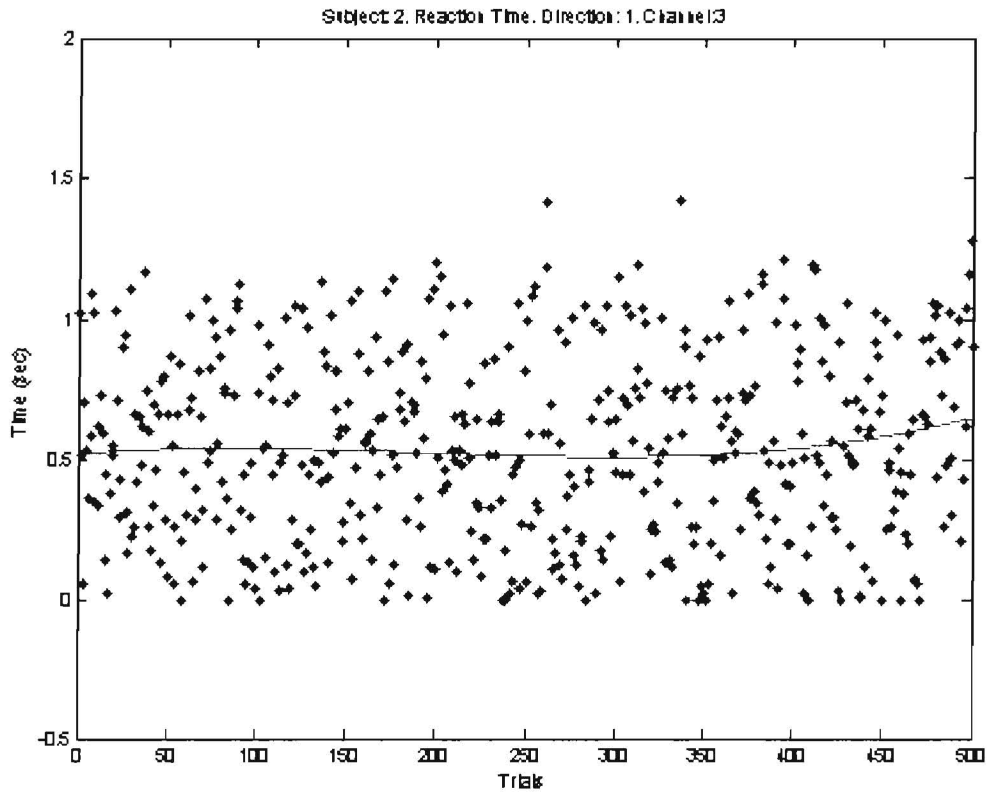

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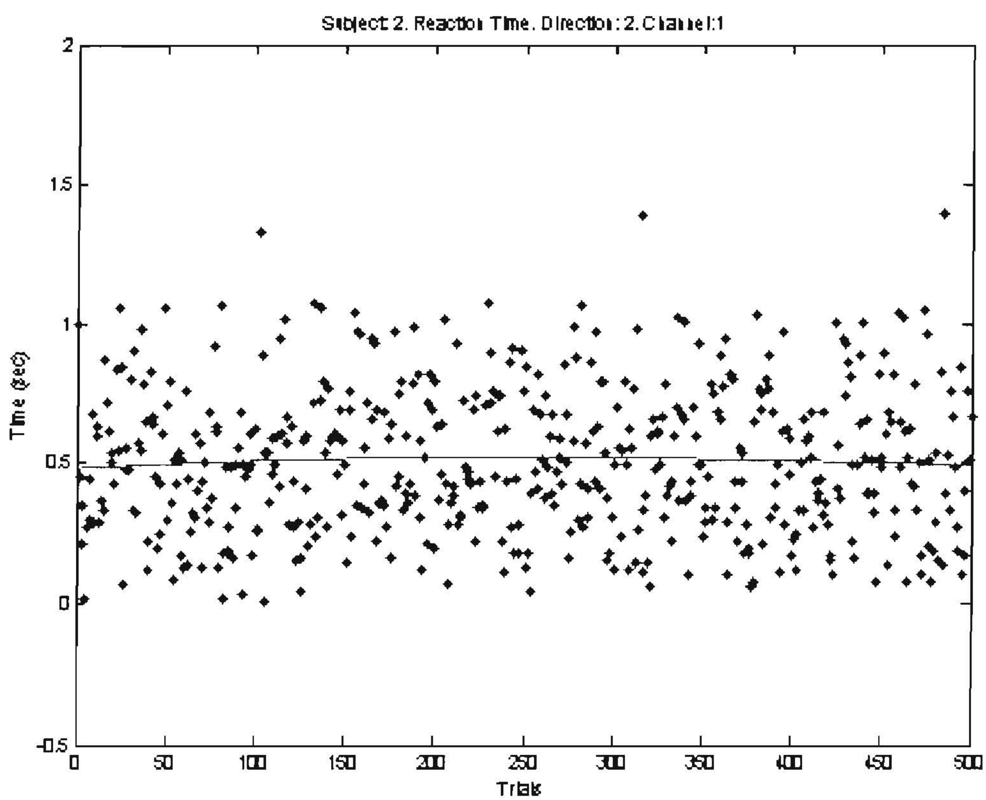

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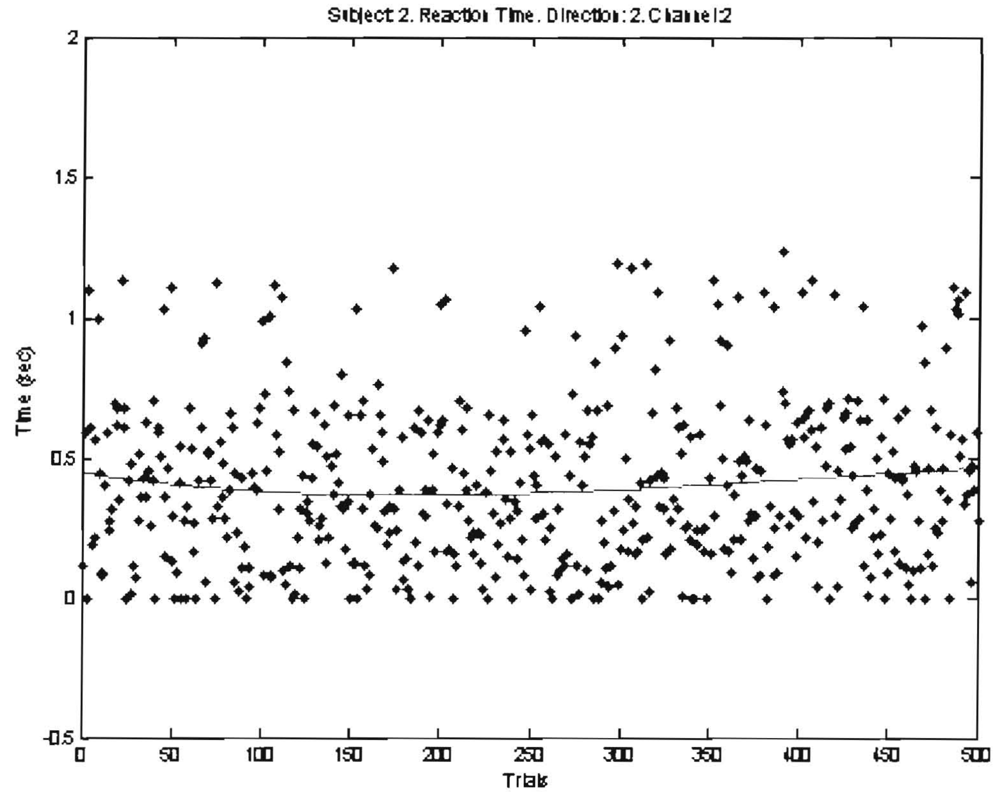
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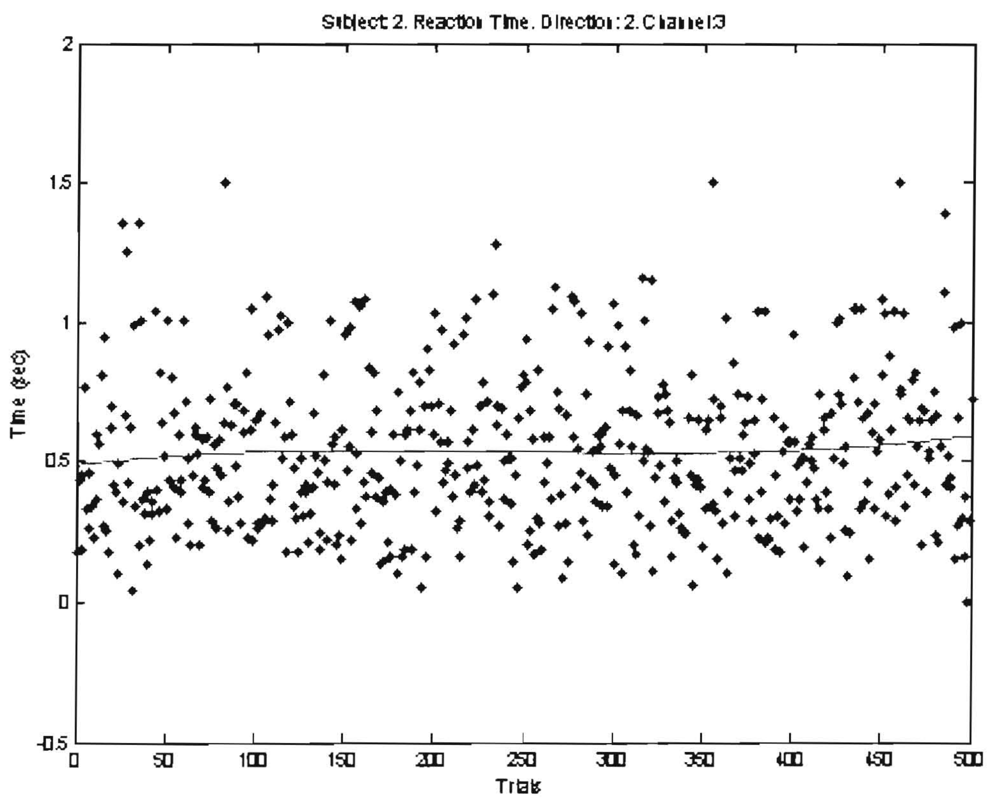
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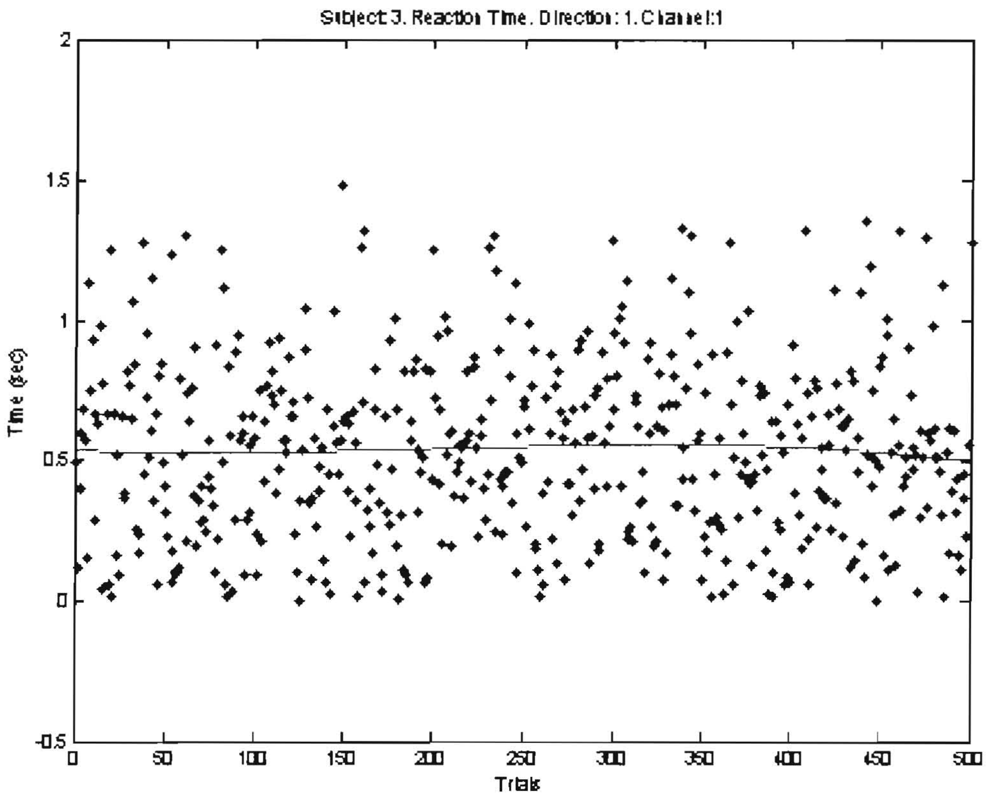

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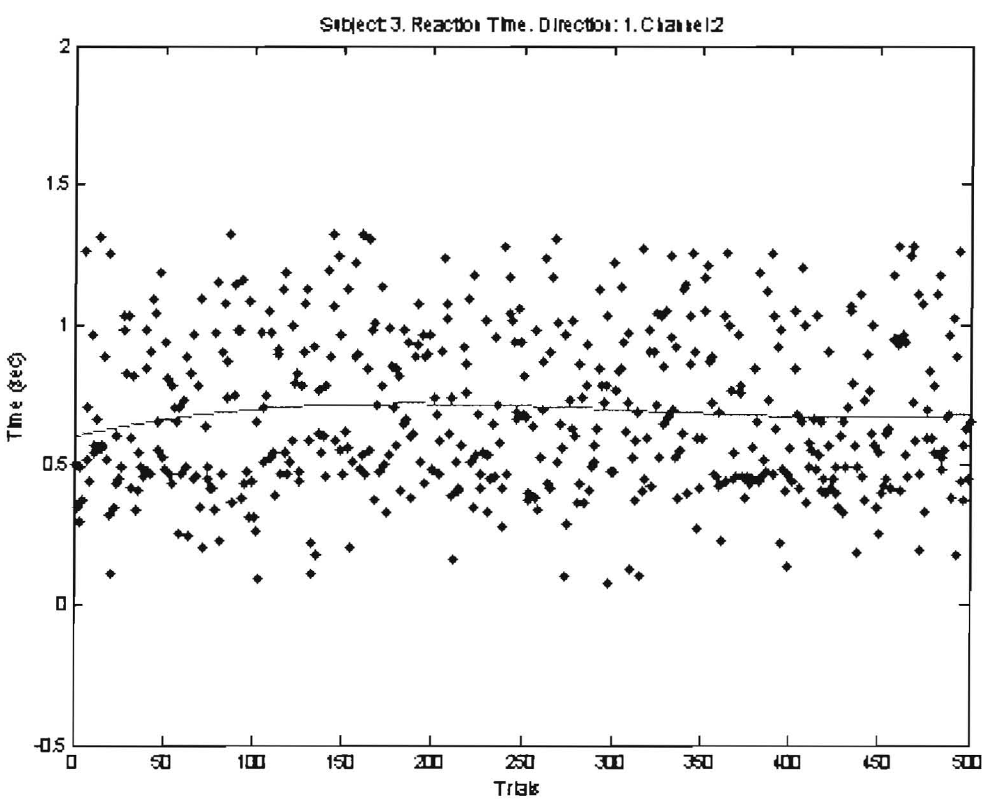

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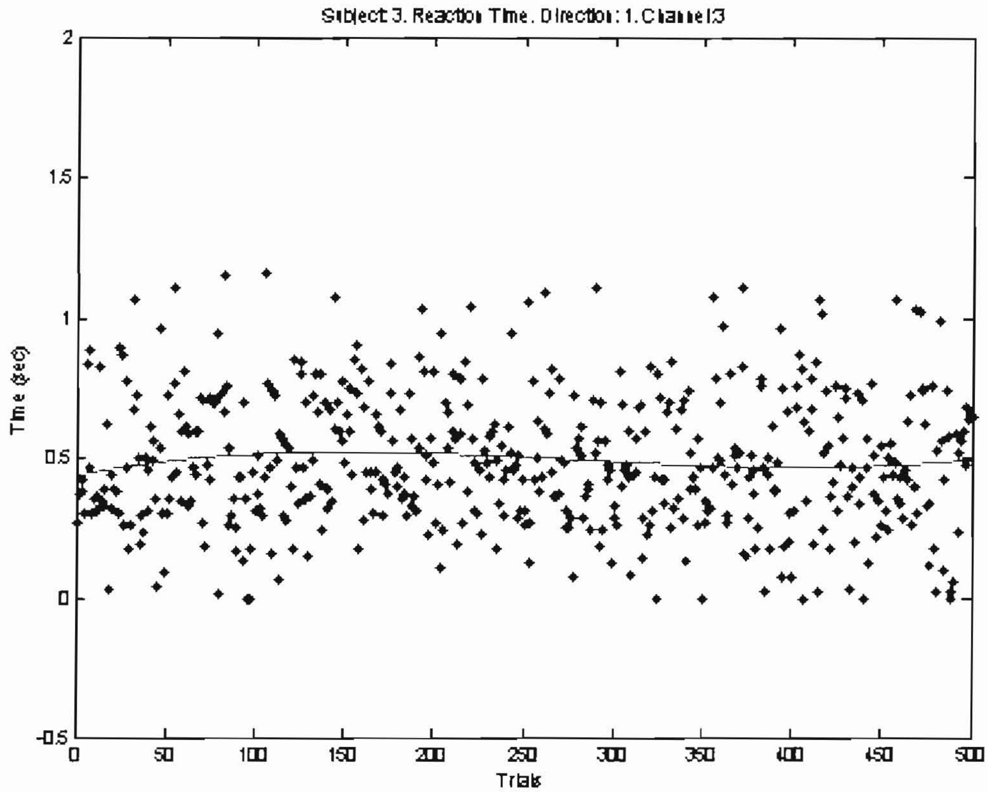
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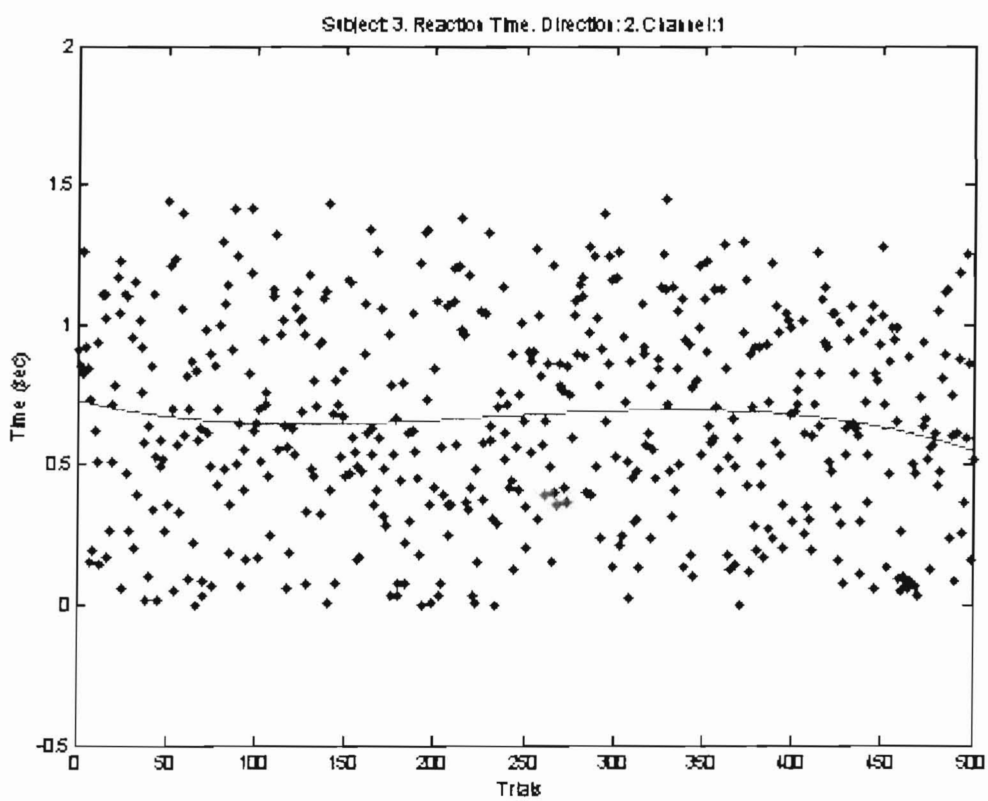
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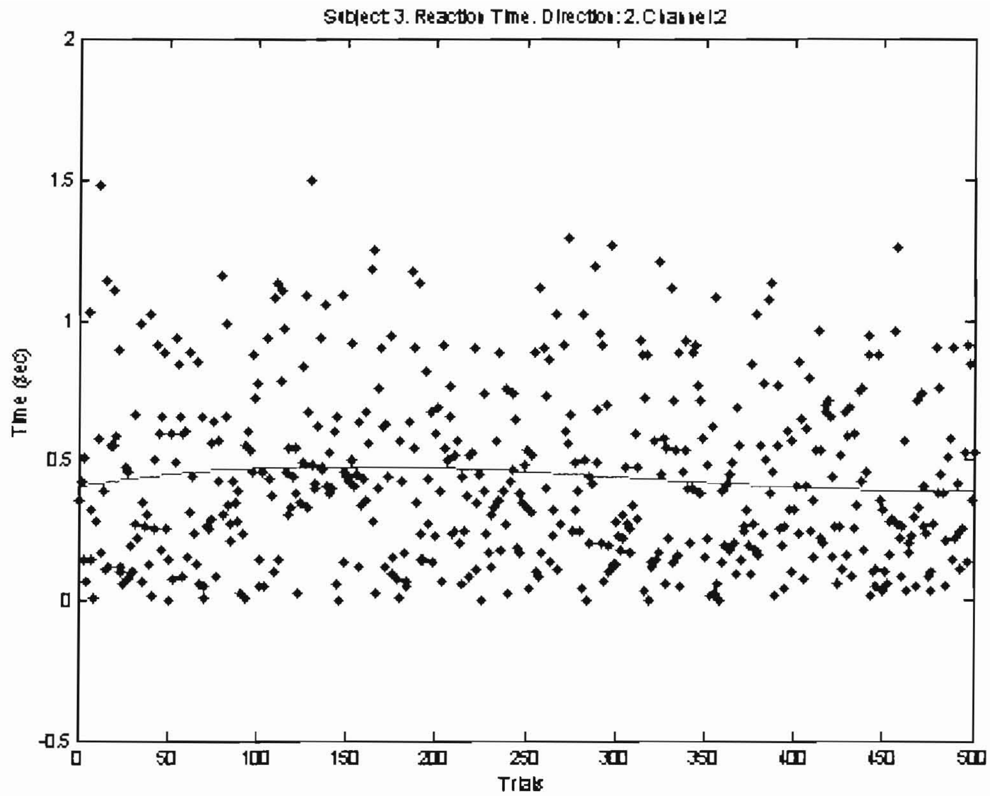

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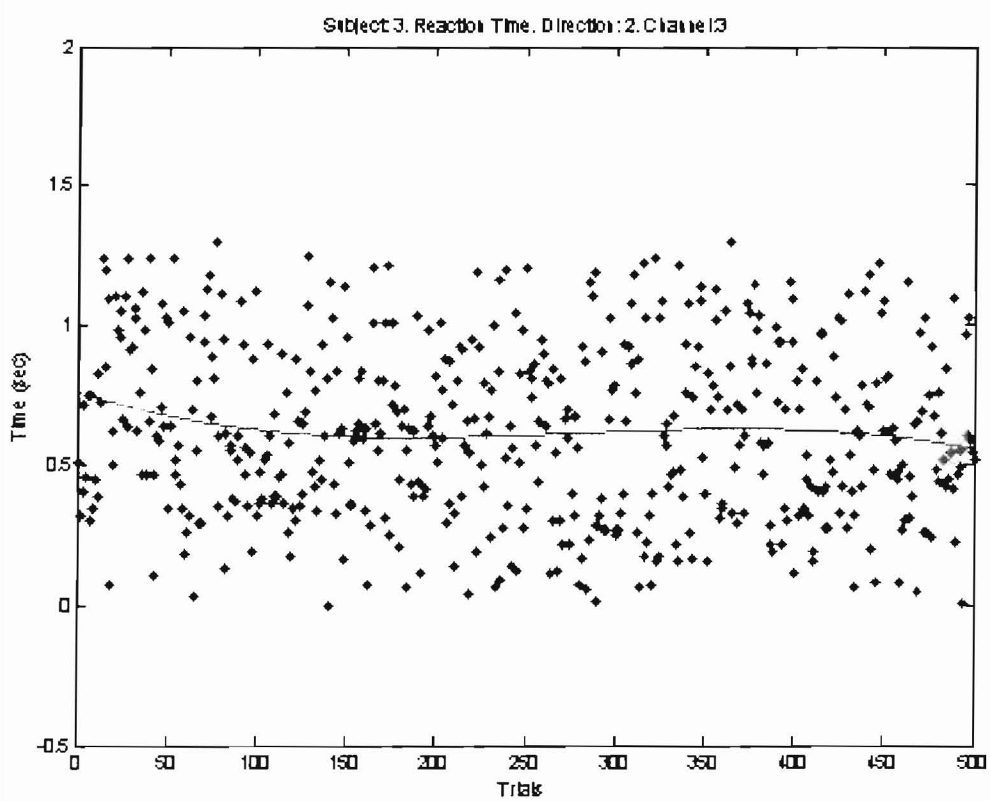

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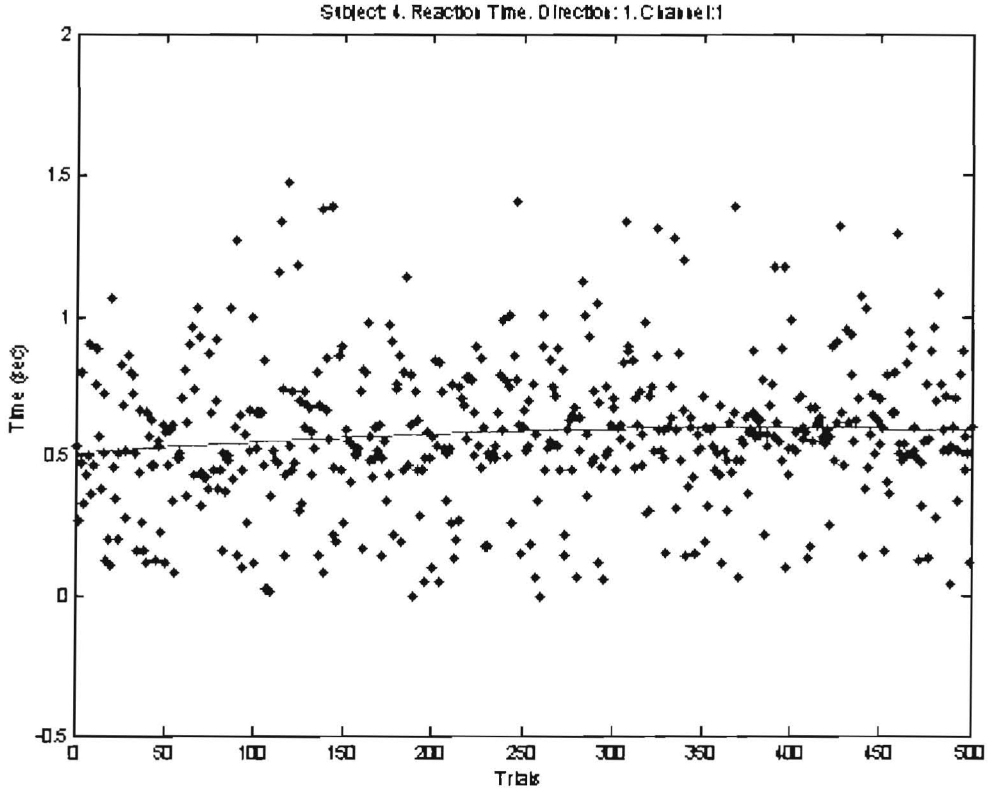
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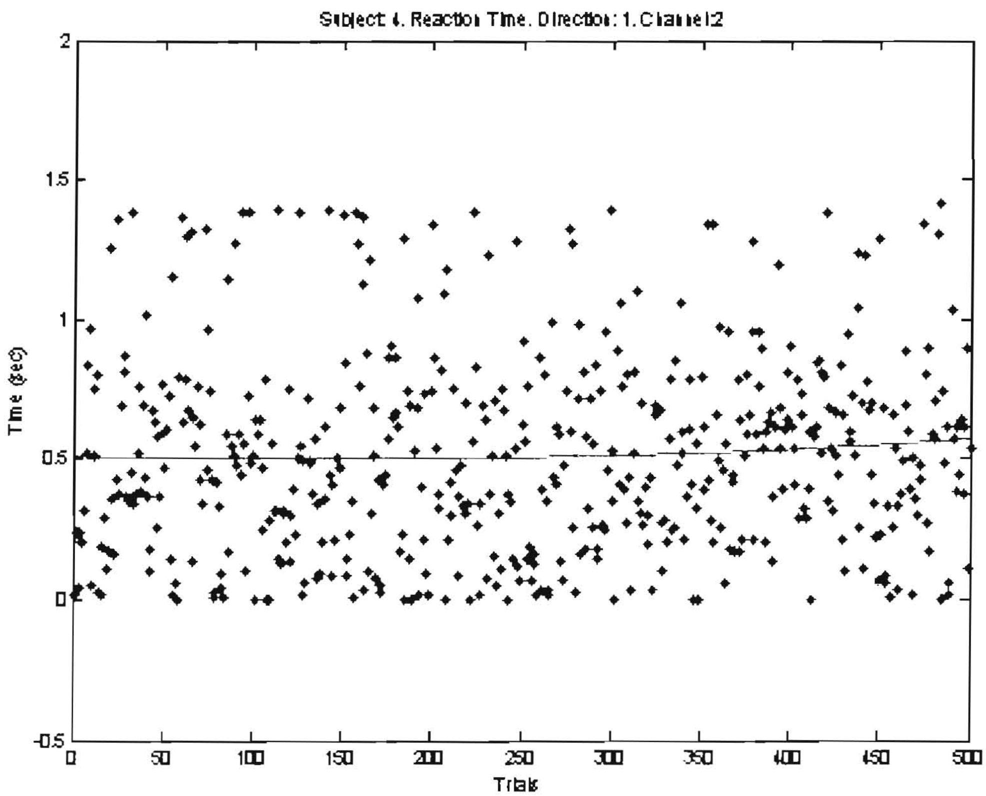
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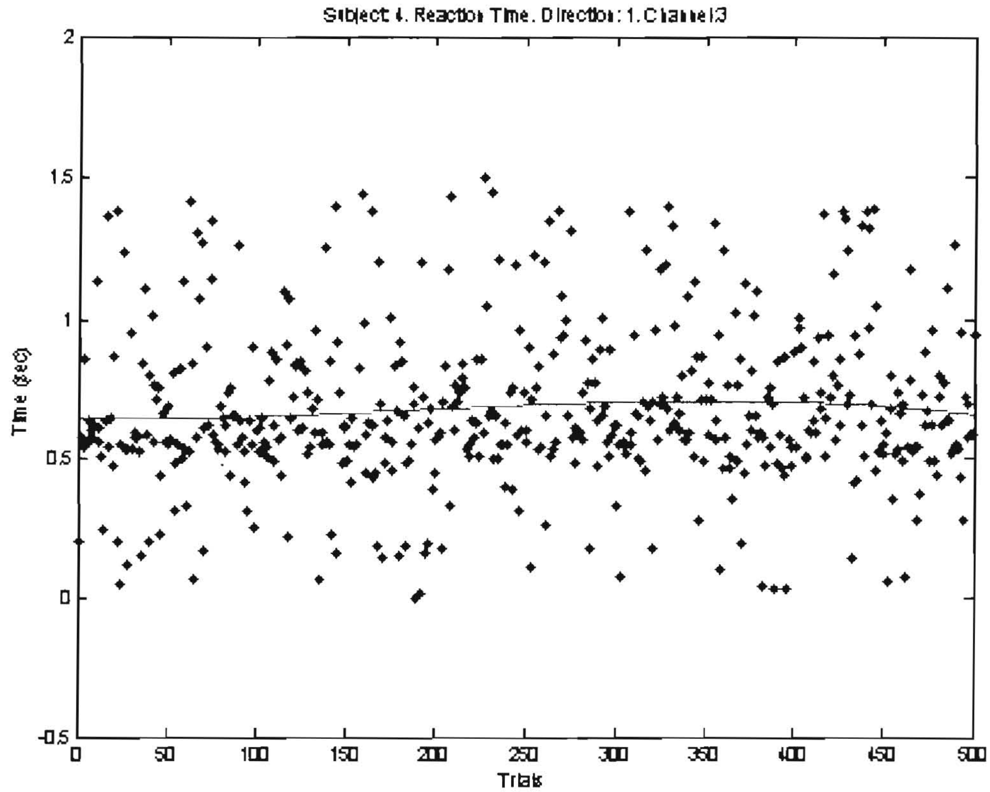
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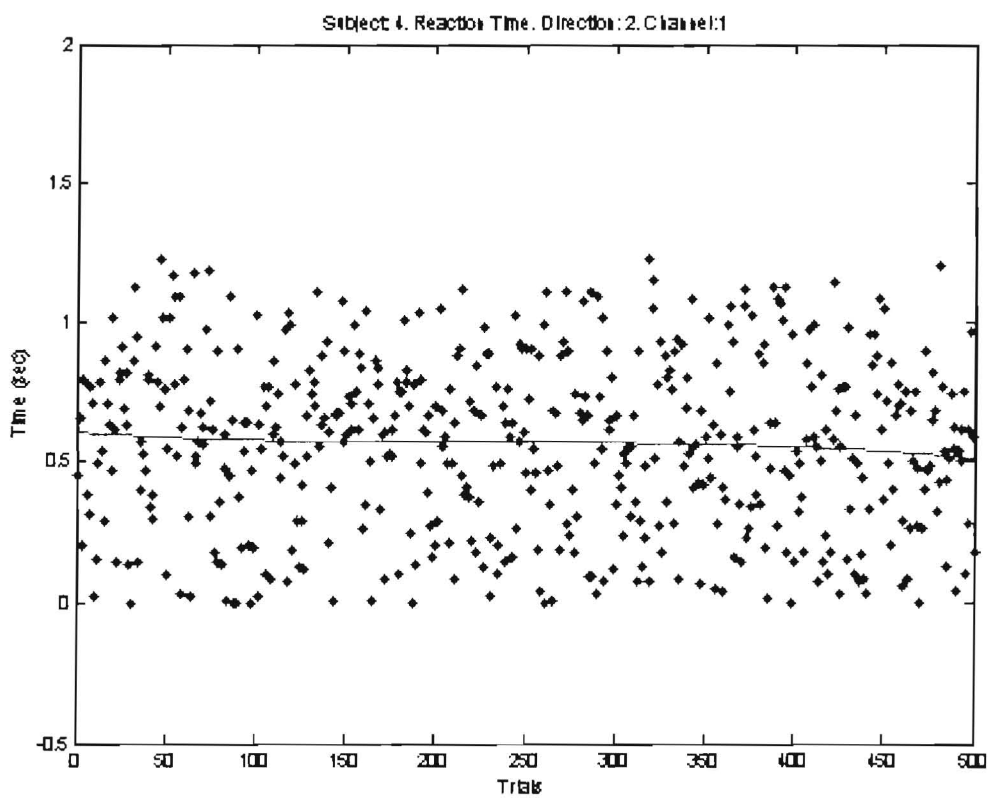
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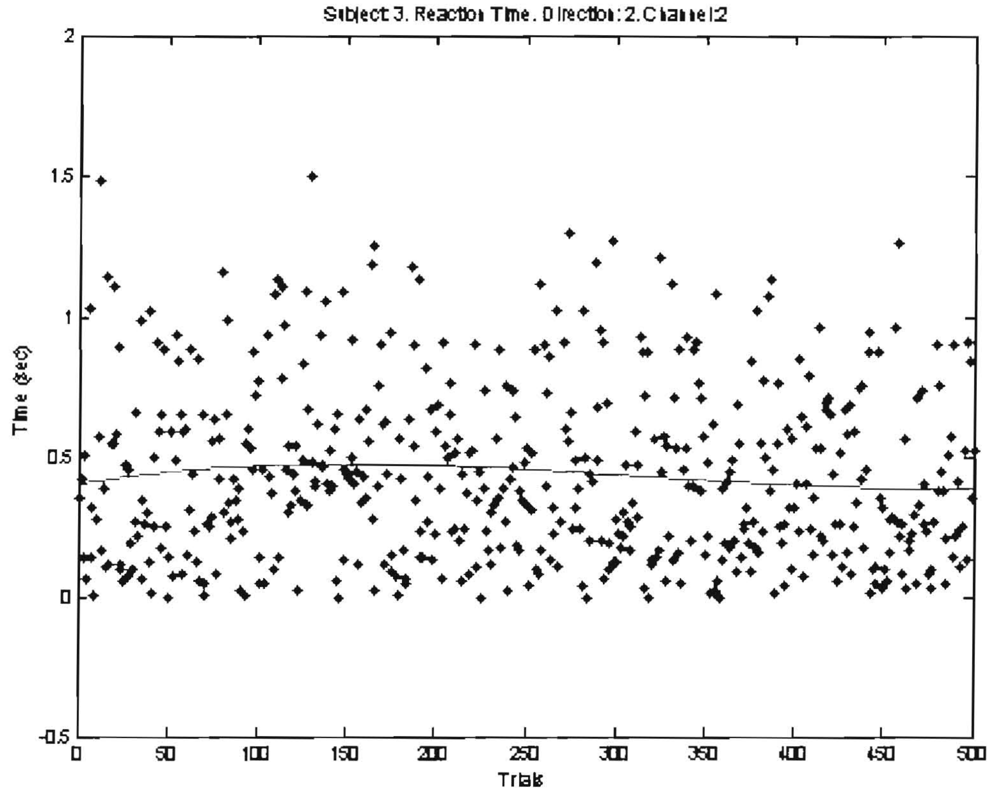
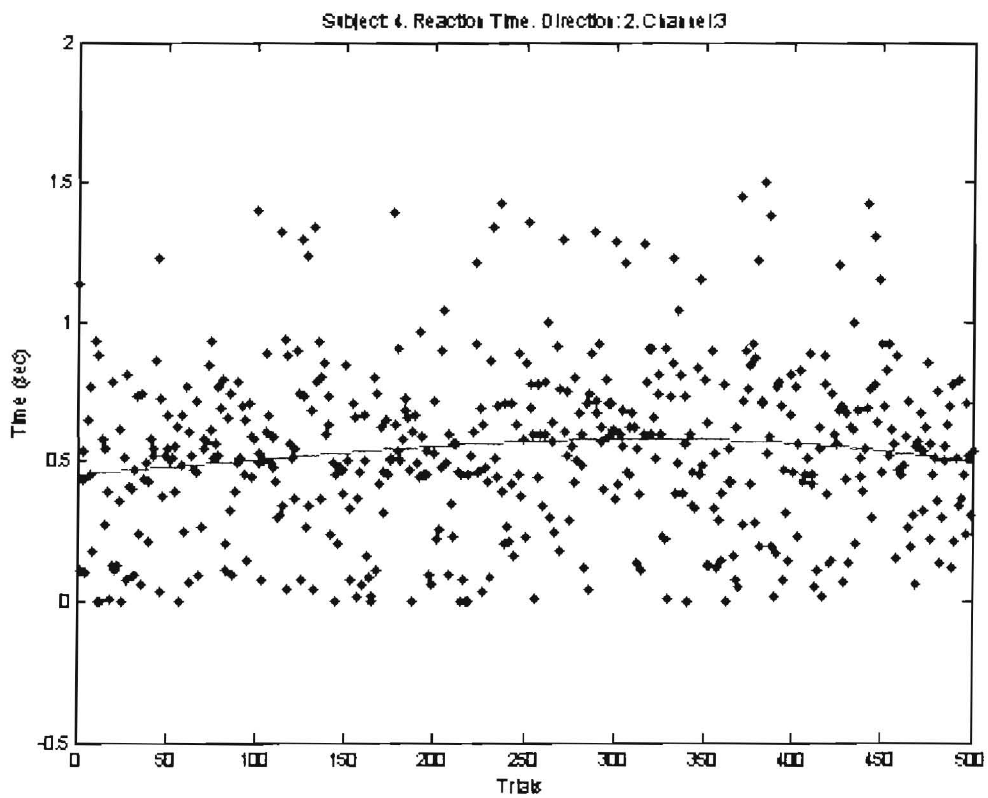
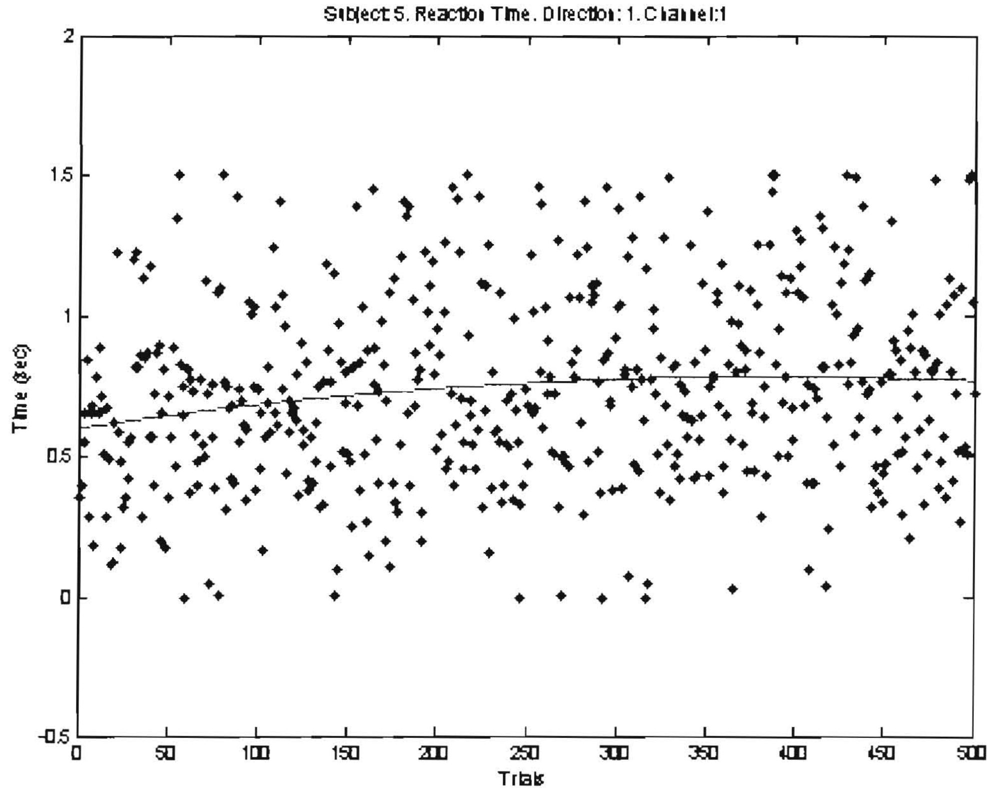
450
500

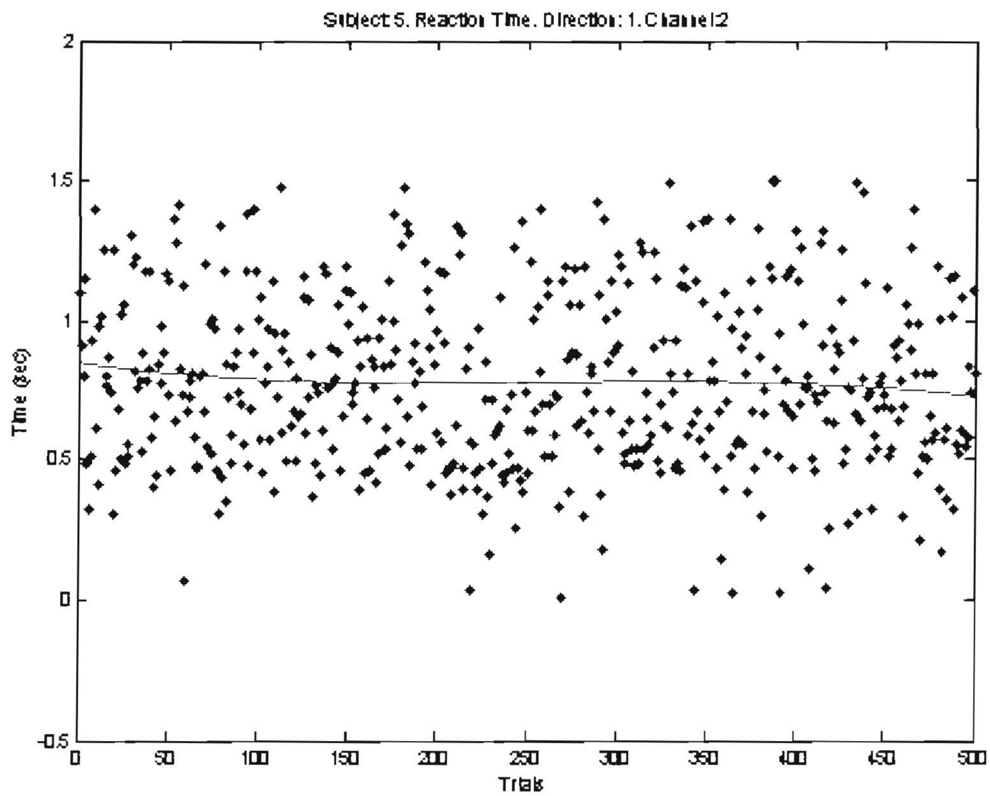


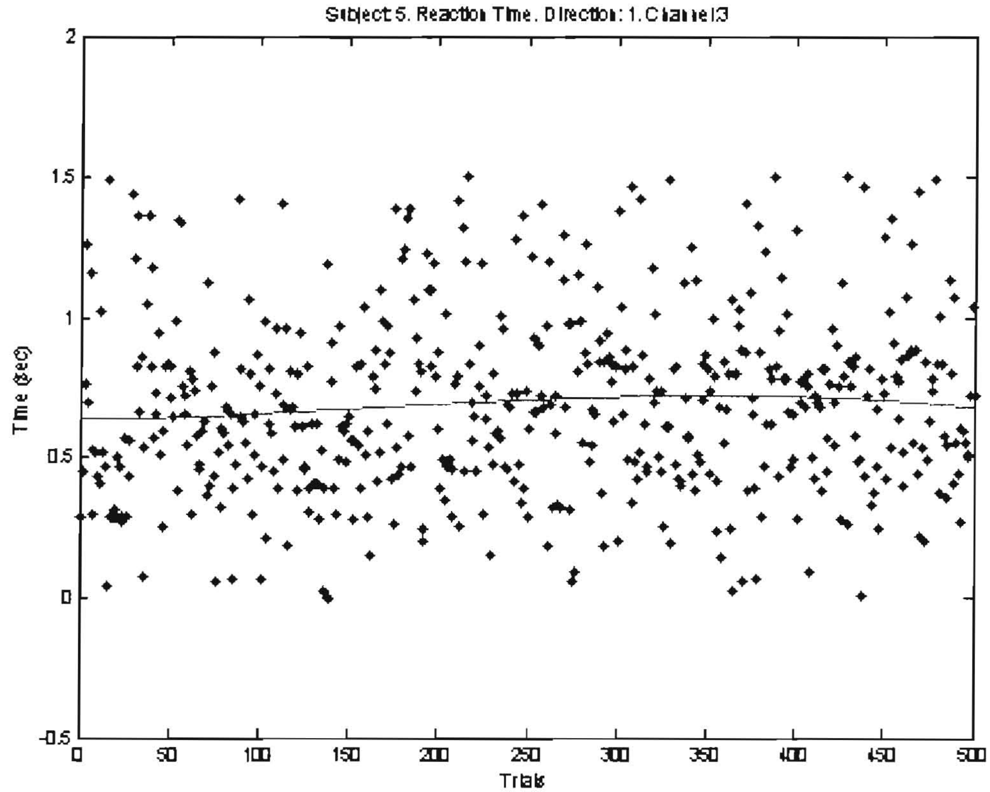
Subject 3. Reaction Time. Direction: 2. Channel 2
Time (sec)
Trials



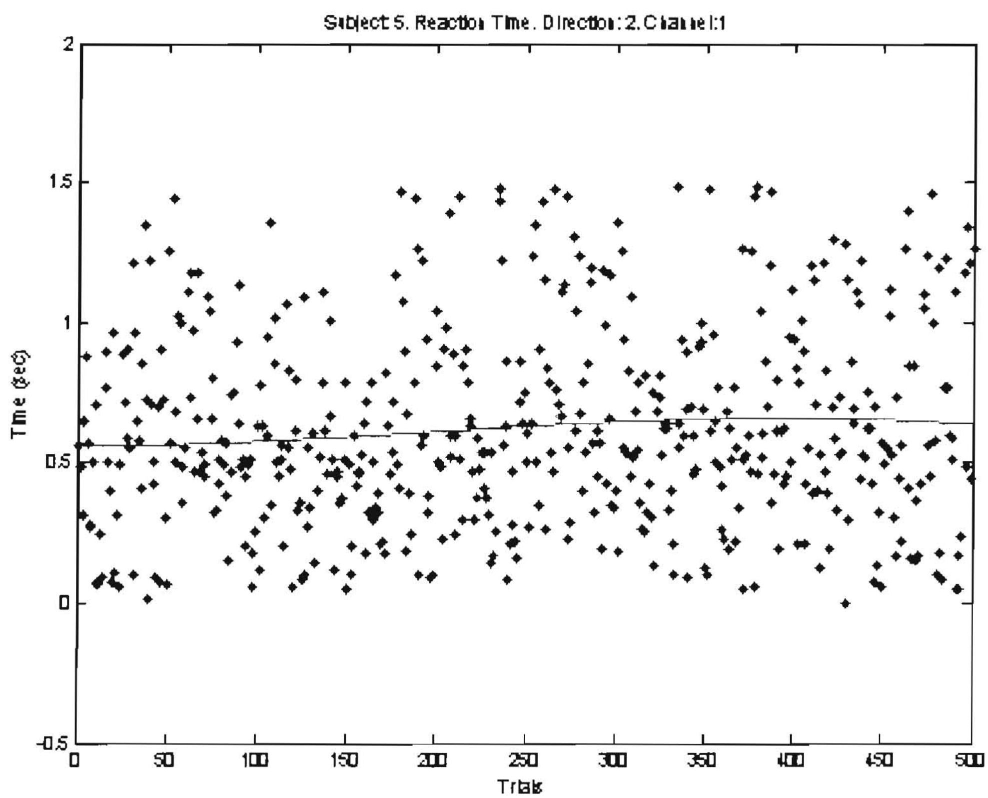
Subject 4. Reaction Time. Direction: 2. Channel 3
Time (sec)
Trials


Subject 5. Reaction Time. Direction: 1. Channel:1
Time (sec)
Trials
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
450
500

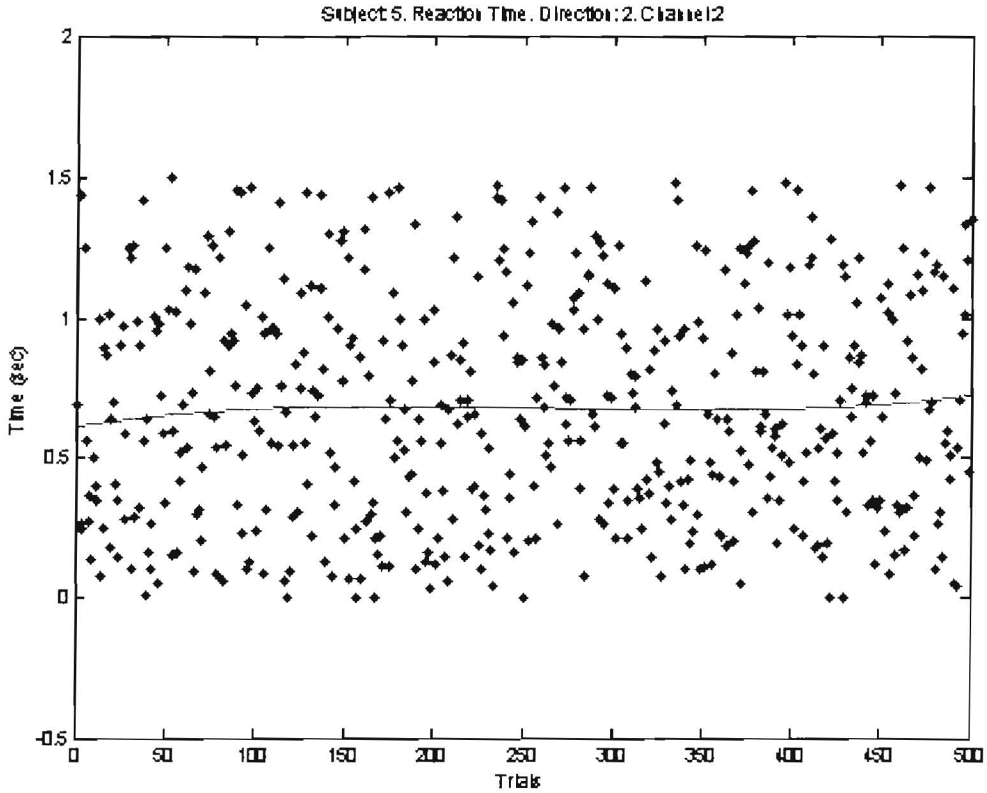

Subject 5. Reaction Time. Direction: 1. Channel:2
Time (sec)
Trials
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
450
500

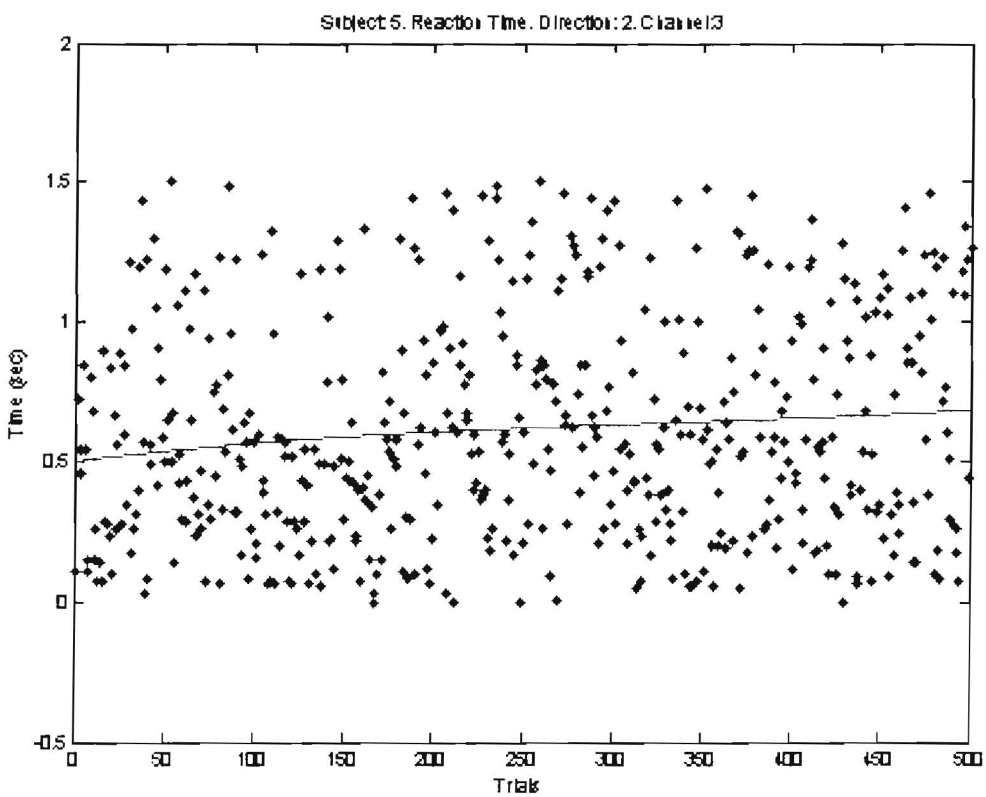


Subject 5. Reaction Time. Direction: 1. Channel 3
Time (sec)
Trials
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
450
500

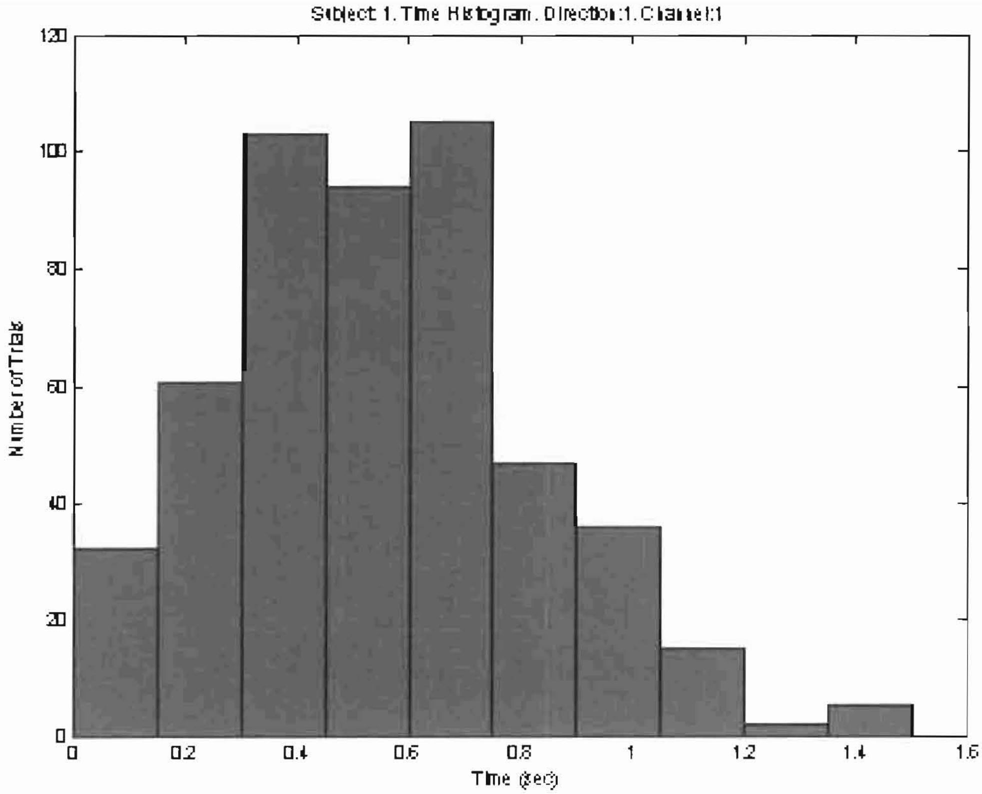


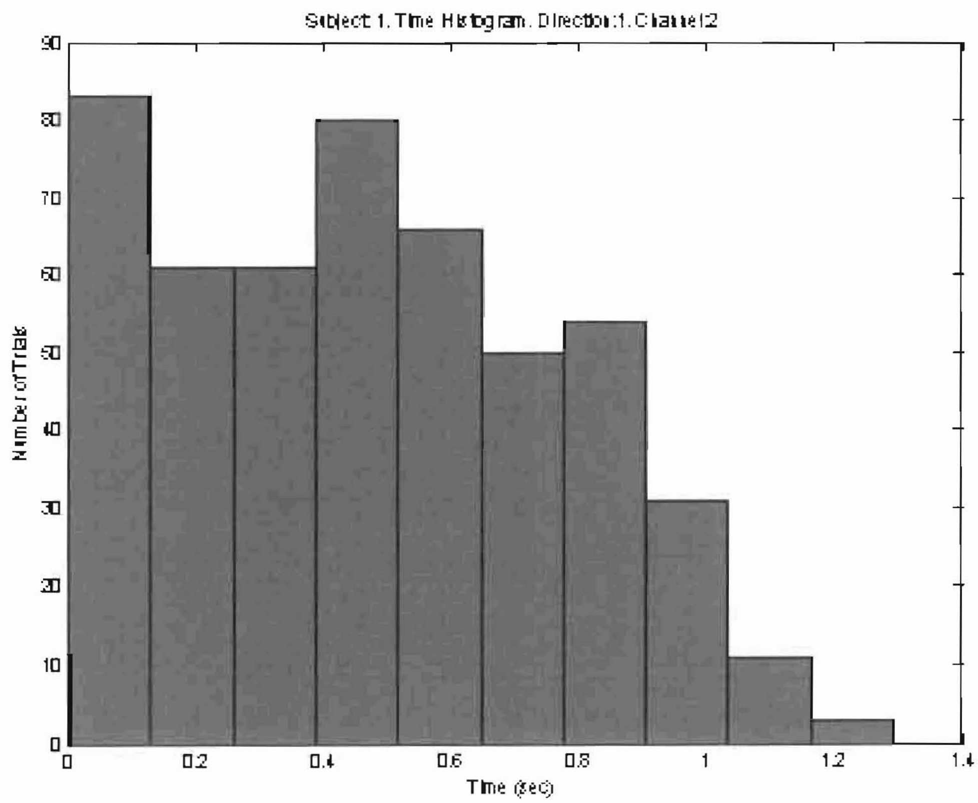
Subject 5. Reaction Time. Direction: 2. Channel 1
Time (sec)
Trials
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
450
500

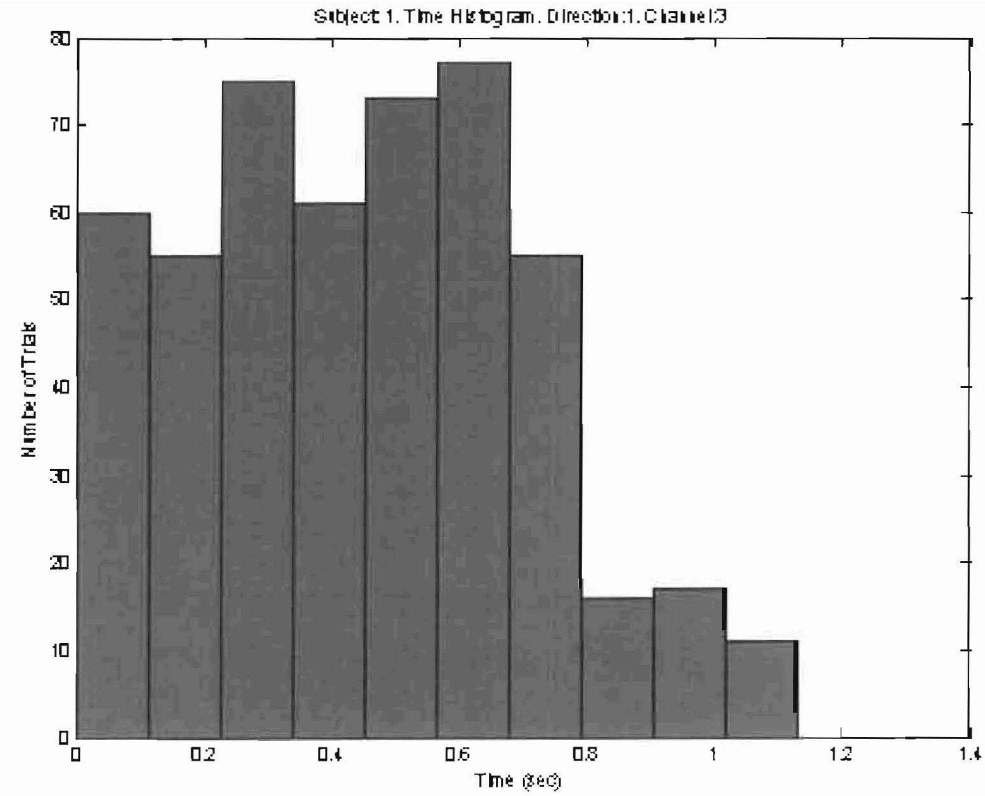

Subject 5. Reaction Time. Direction: 2. Channel 2
Time (sec)
Trials
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
450
500

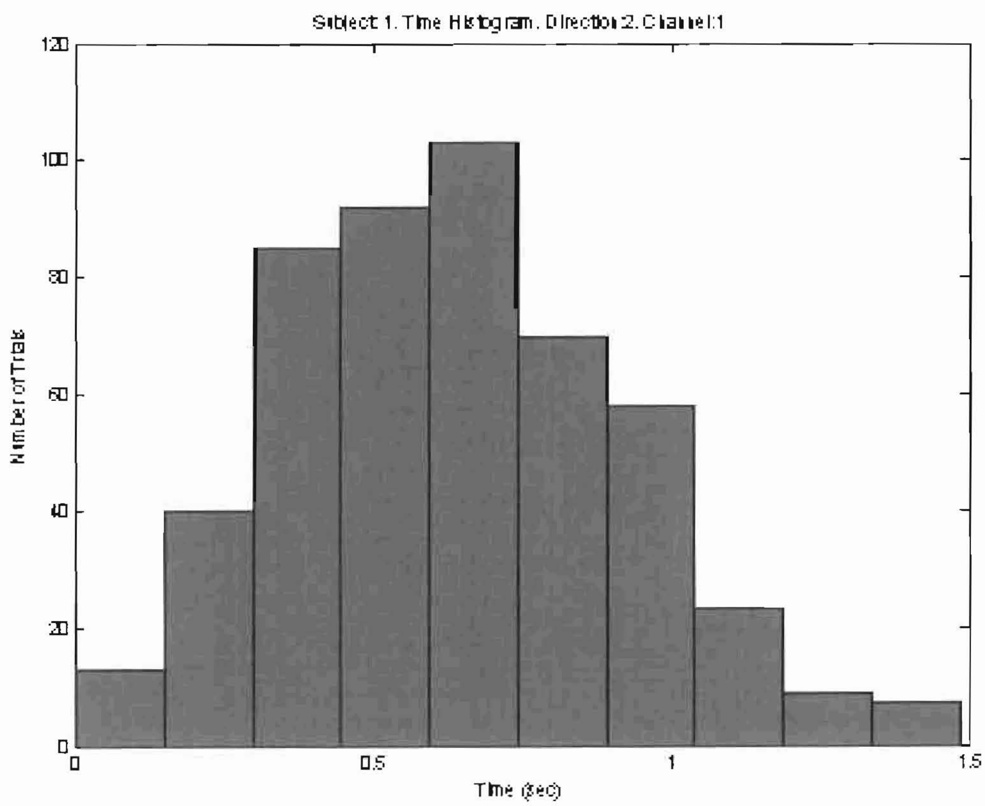

Subject 5. Reaction Time. Direction: 2. Channel 3
Time (sec)
Trials
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
450
500

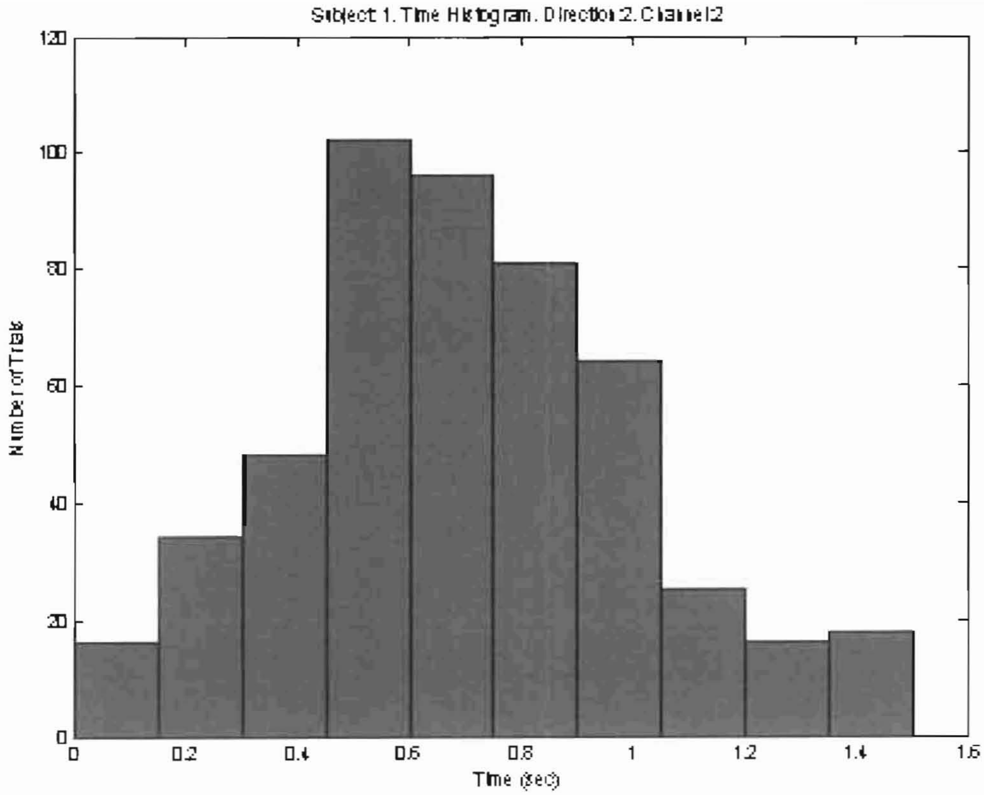
APPENDIX 2: REACTION TIME HISTOGRAM RESULTS

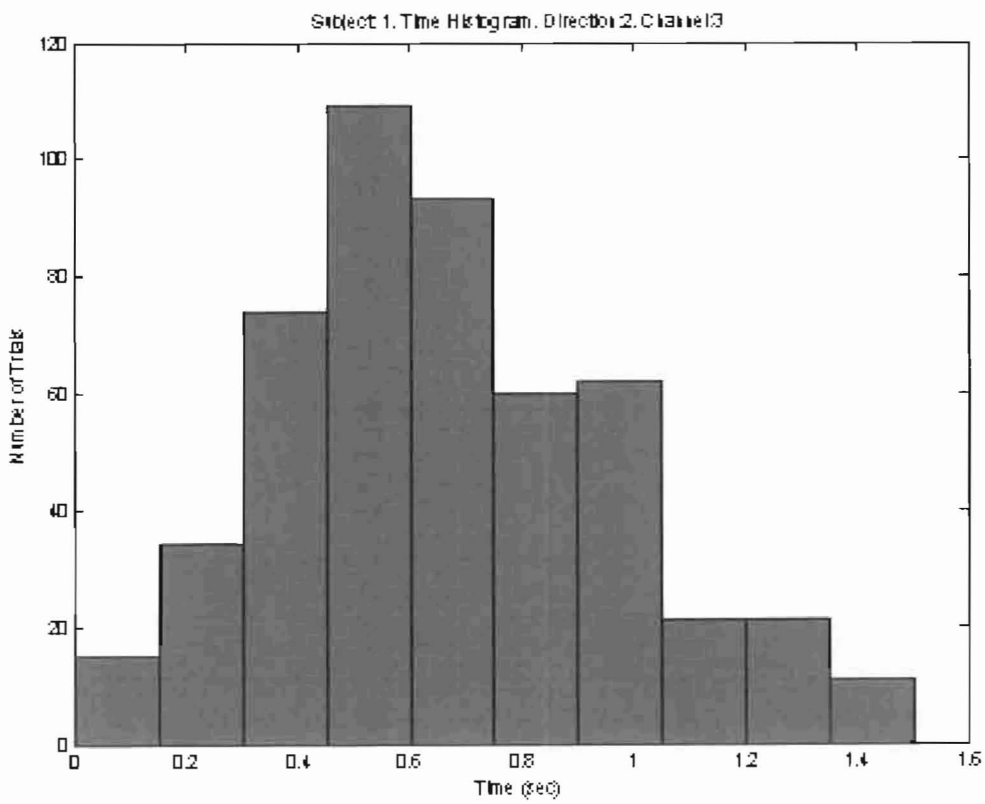

Subject 1. Time Histogram. Direction:1. Channel:1
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

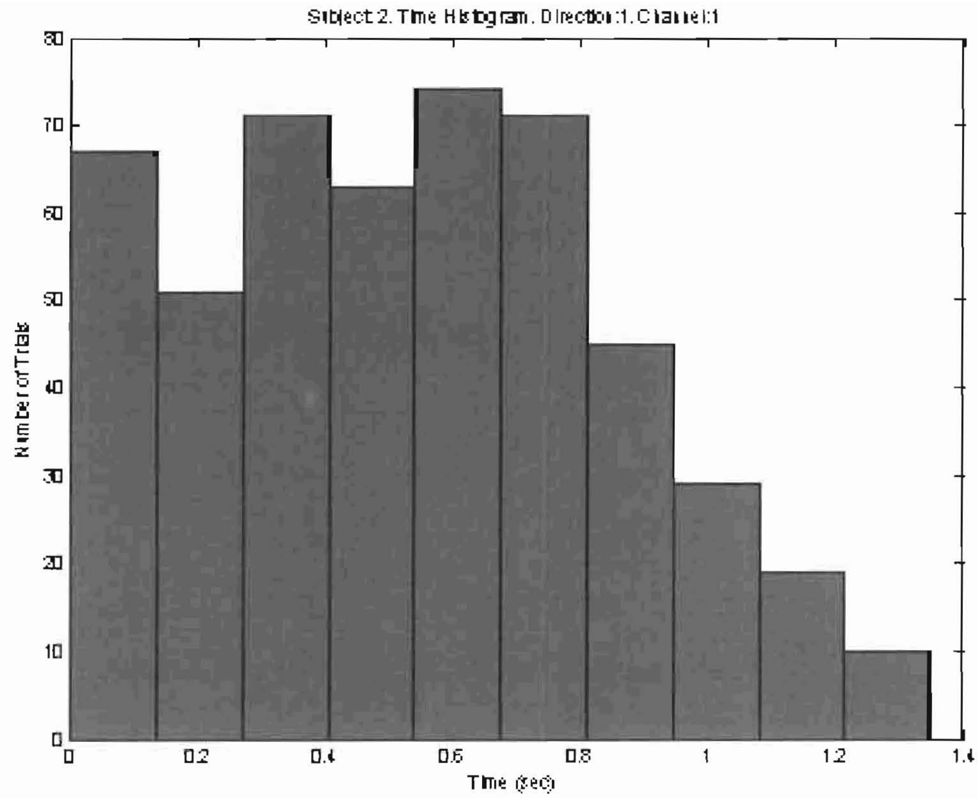

Subject 1. Time Histogram. Direction:1. Channel:2
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
90
0
0.2
0.4
0.6
0.8
1
1.2
1.4

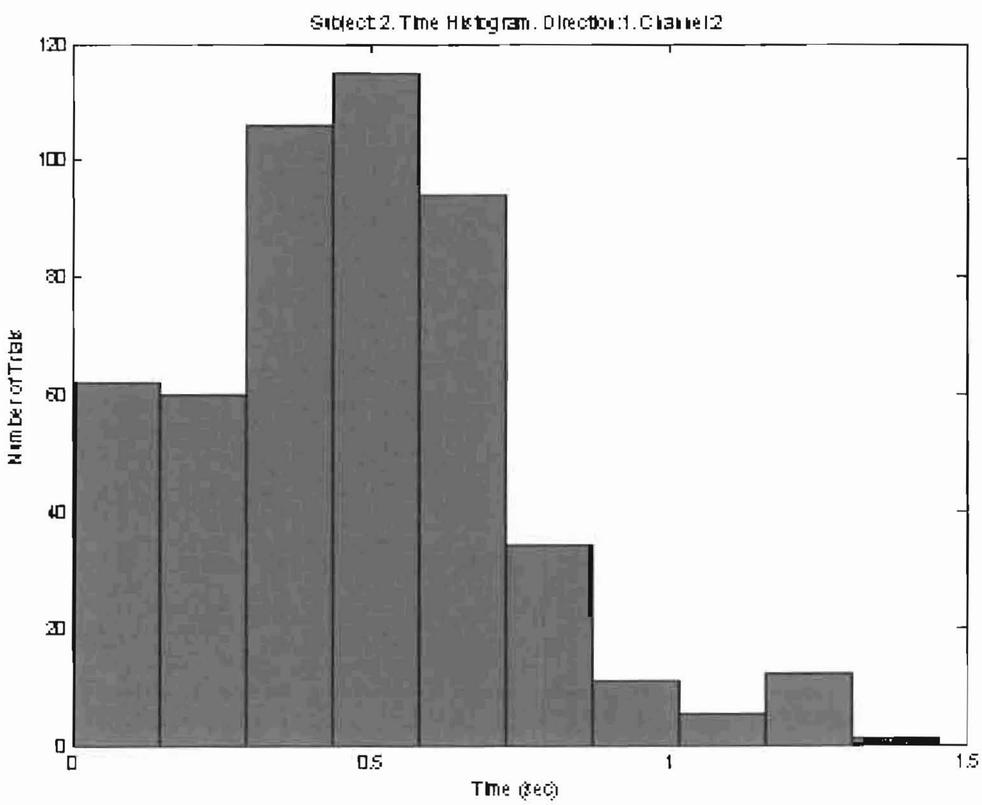

Subject 1. Time Histogram. Direction:1. Channel:3
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
0.2
0.4
0.6
0.8
1
1.2
1.4

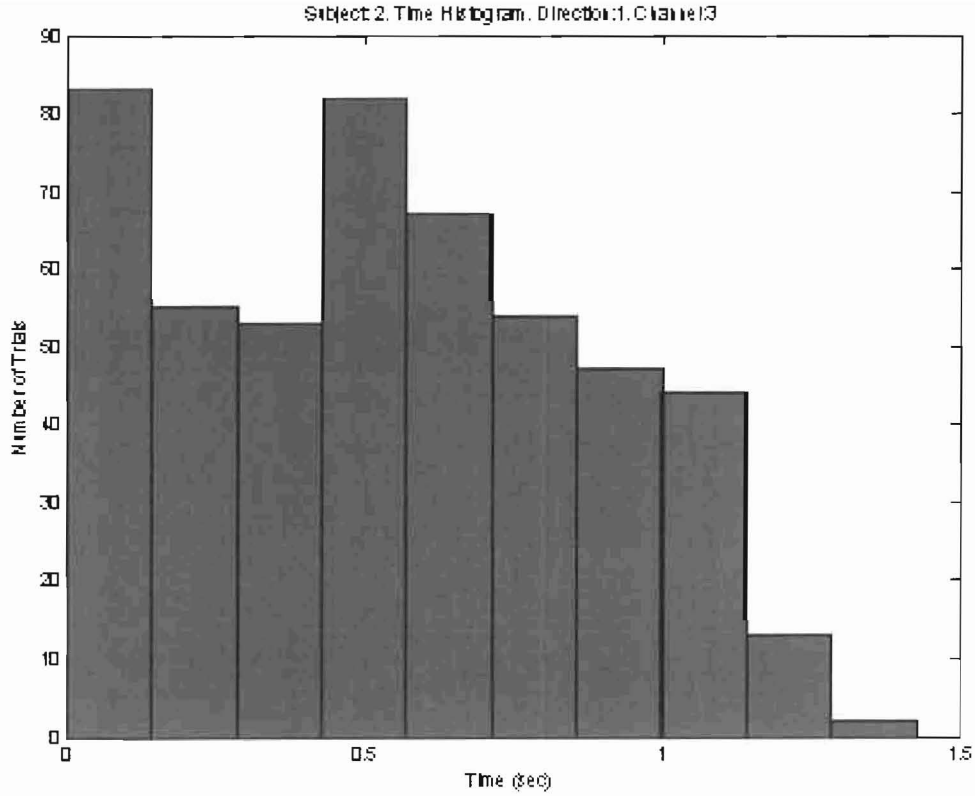

Subject 1. Time Histogram. Direction:2. Channel:1
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0.5
1
1.5

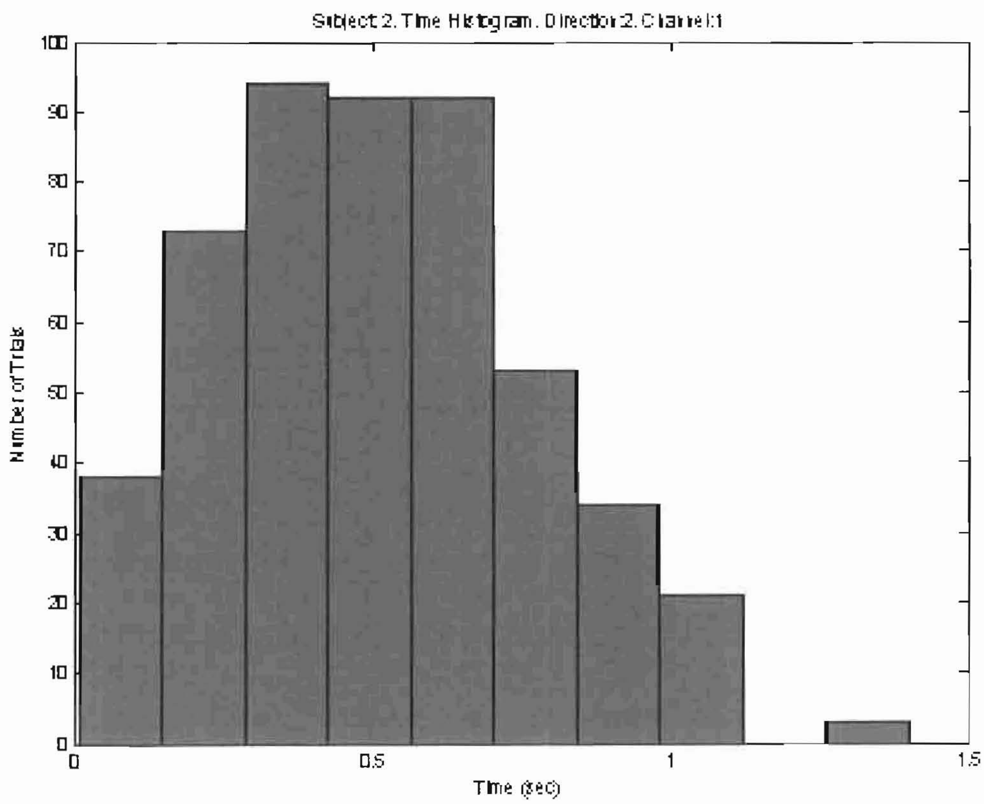

Subject 1. Time Histogram. Direction 2. Channel 2
Number of Trials
Time (sec)

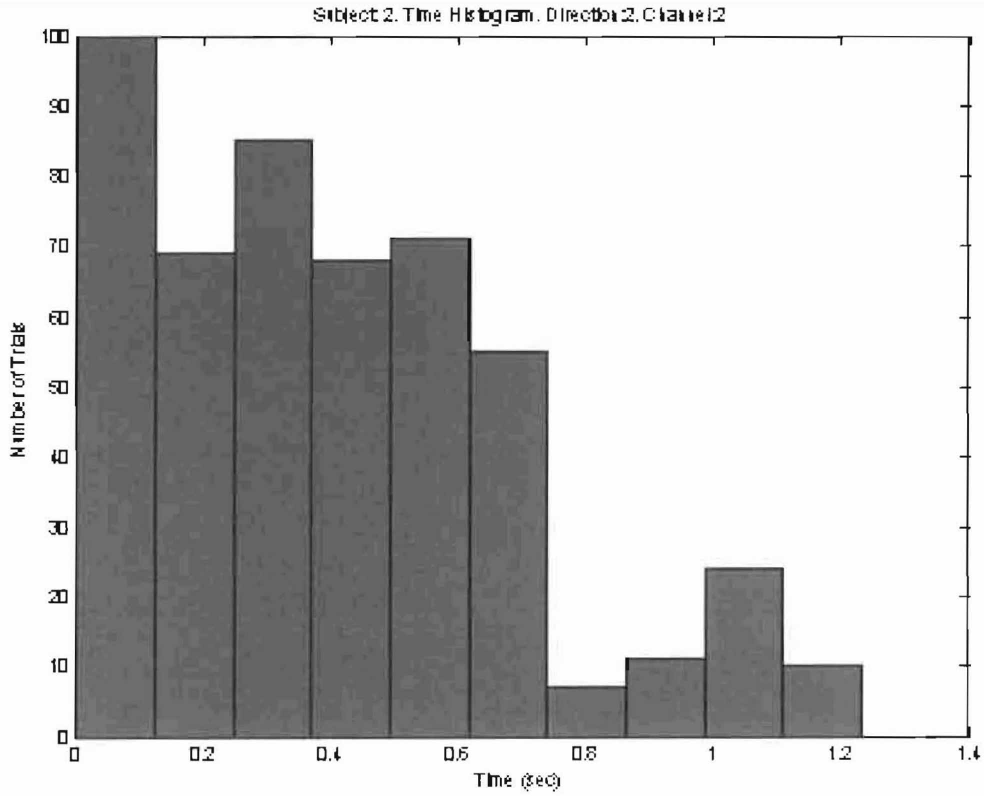

Subject 1. Time Histogram. Direction 2. Channel 3
Number of Trials
Time (sec)

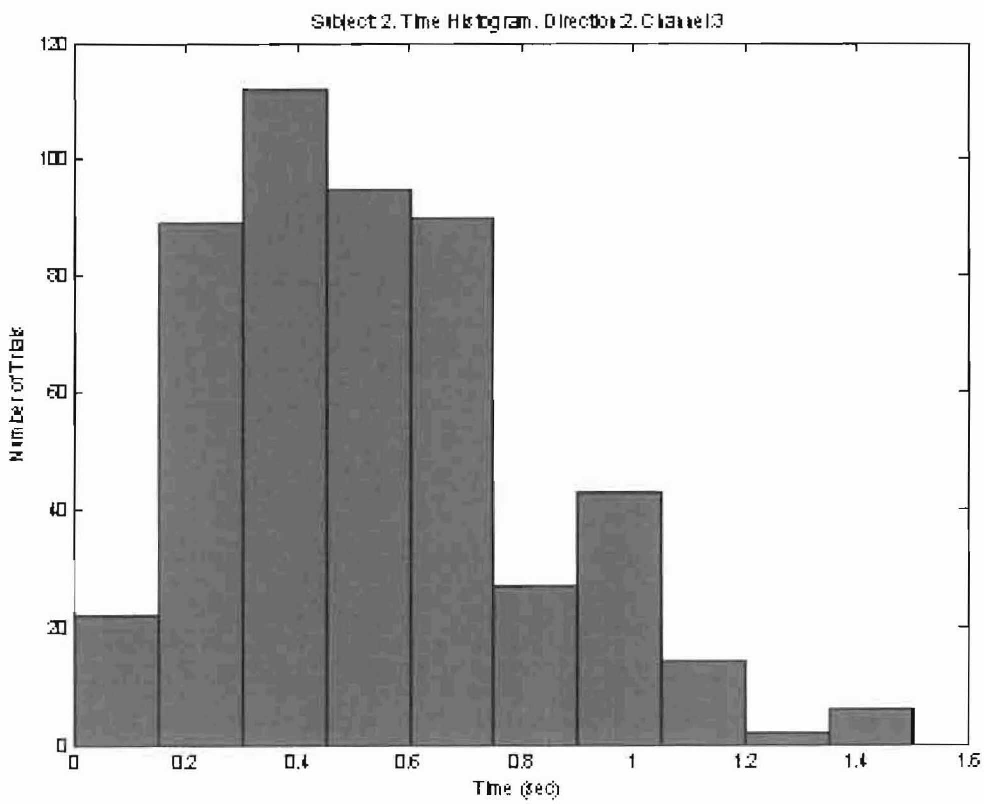

Subject 2. Time Histogram. Direction:1. Channel:1
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
0.2
0.4
0.6
0.8
1
1.2
1.4

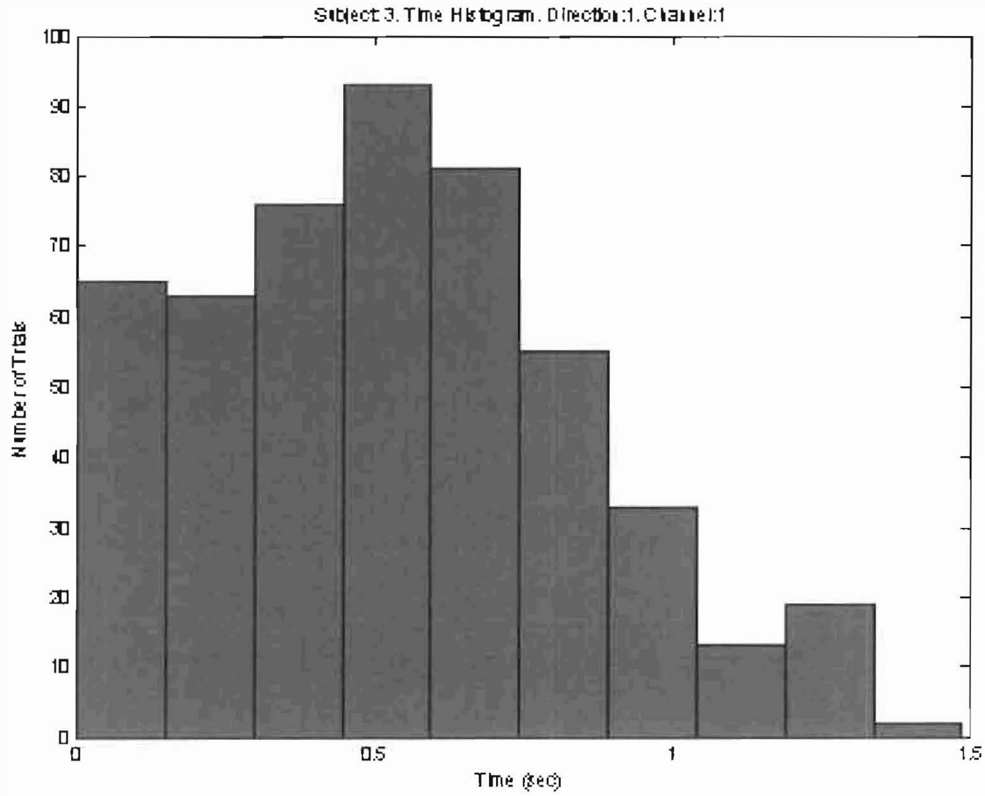

Subject 2. Time Histogram. Direction:1. Channel:2
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0.5
1
1.5

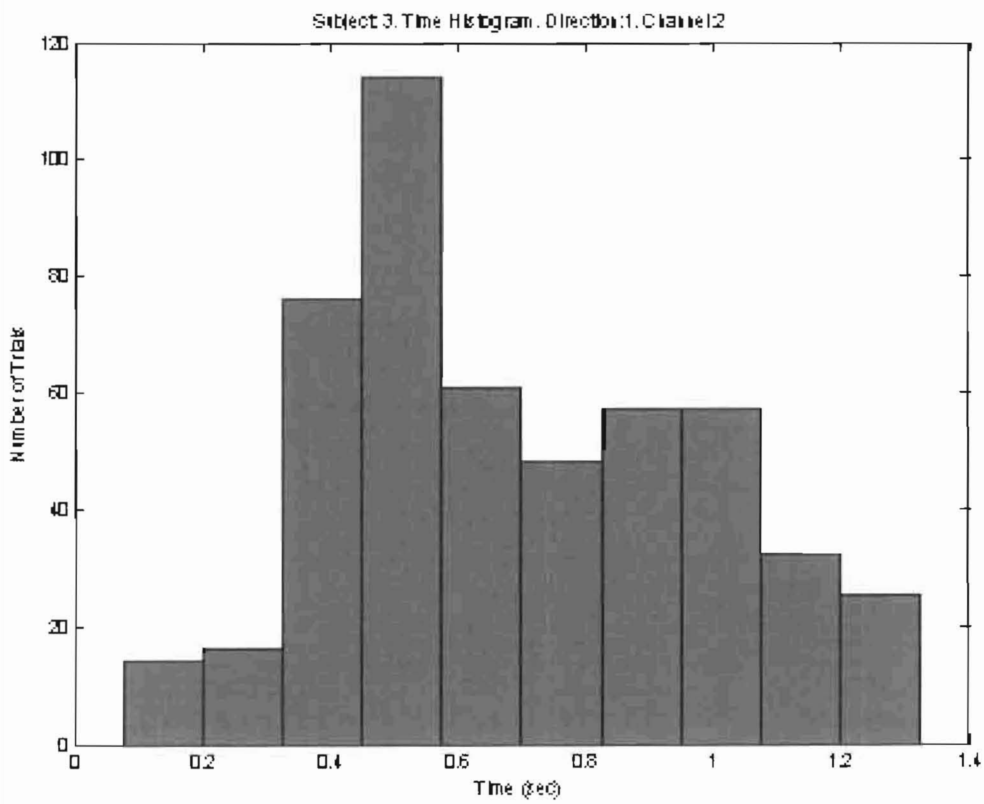

Subject 2. Time Histogram. Direction:1. Channel:3
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
90
0.5
1
1.5

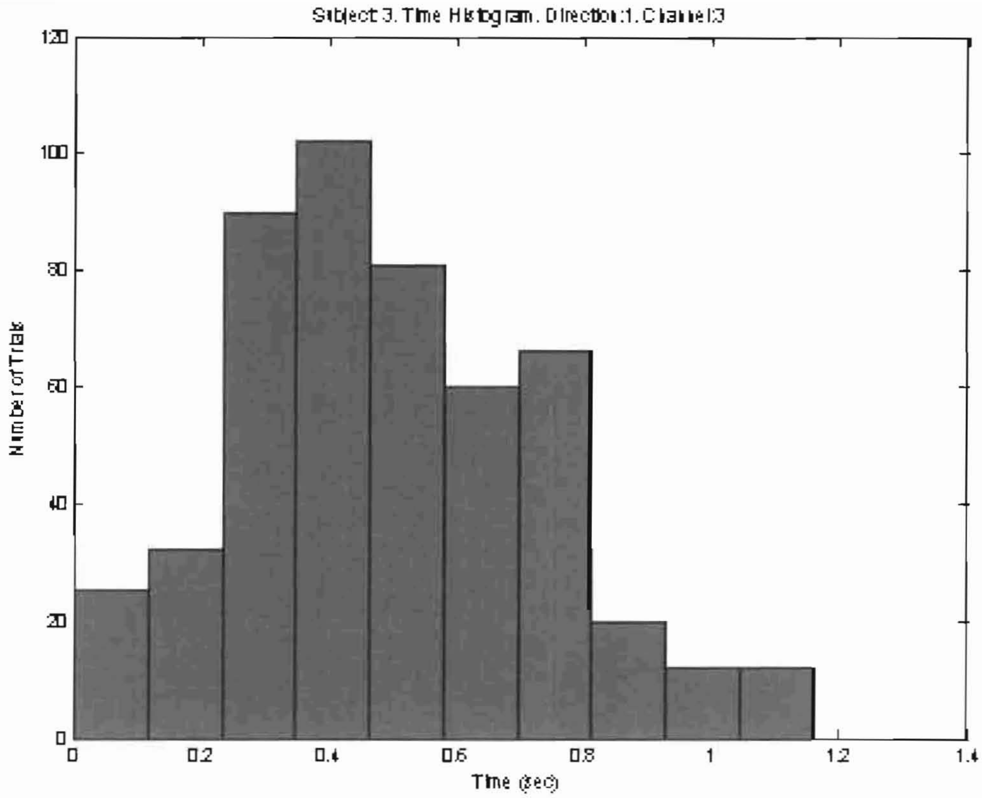

Subject 2. Time Histogram. Direction:2. Channel:1
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
90
100
0.5
1
1.5

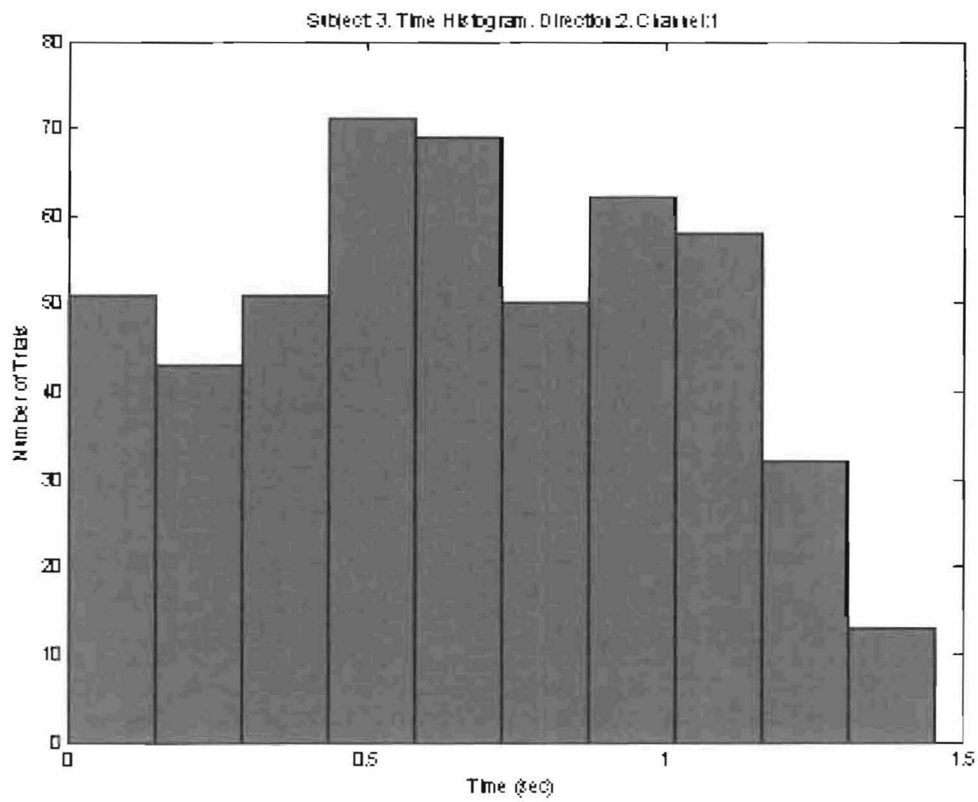

Subject 2. Time Histogram. Direction 2. Channel 2
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
90
100
0.2
0.4
0.6
0.8
1
1.2
1.4

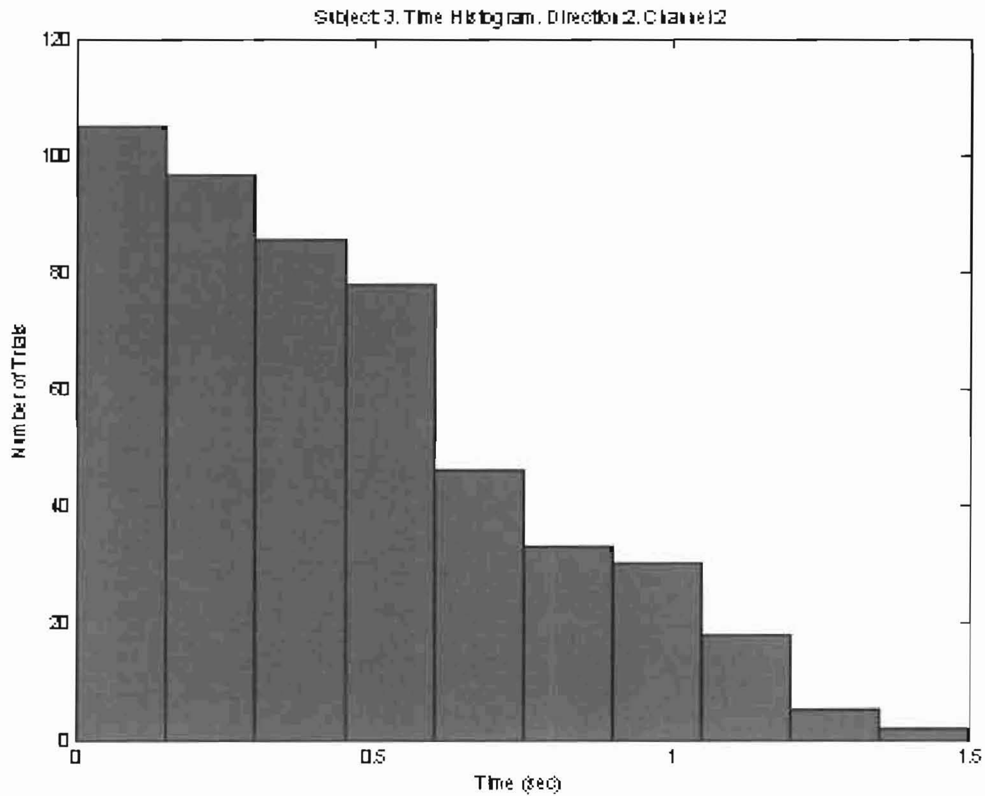

Subject 2. Time Histogram. Direction 2. Channel 3
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

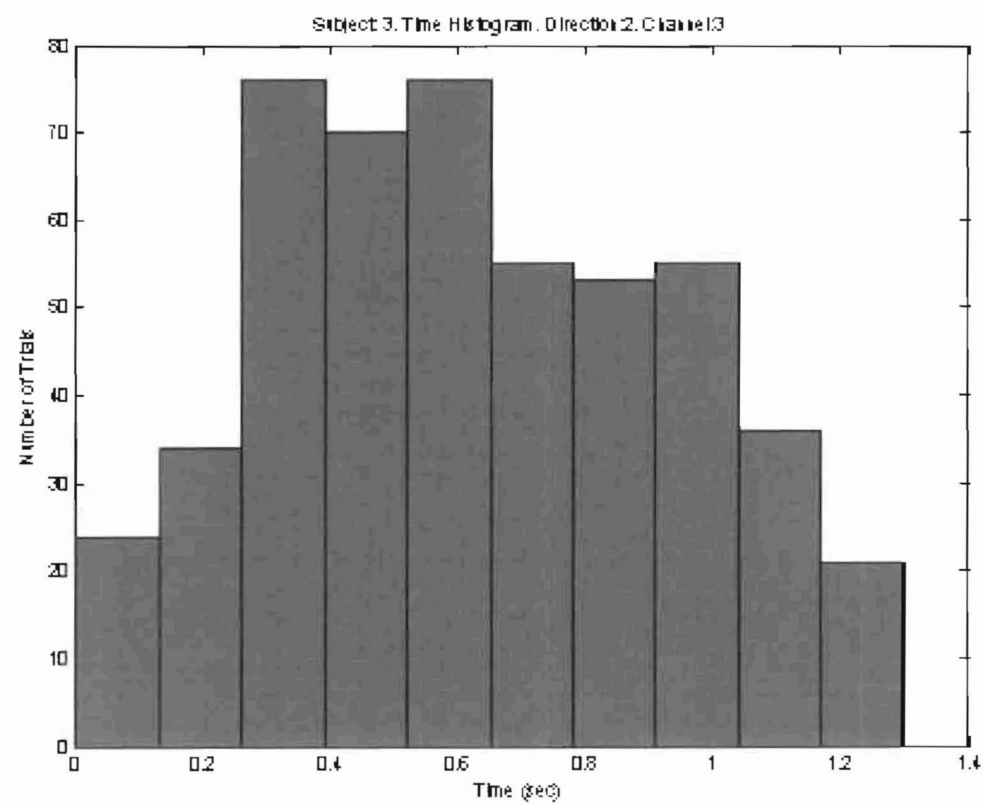

Subject 3. Time Histogram. Direction:1. Channel:1
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
90
100
0.5
1
1.5

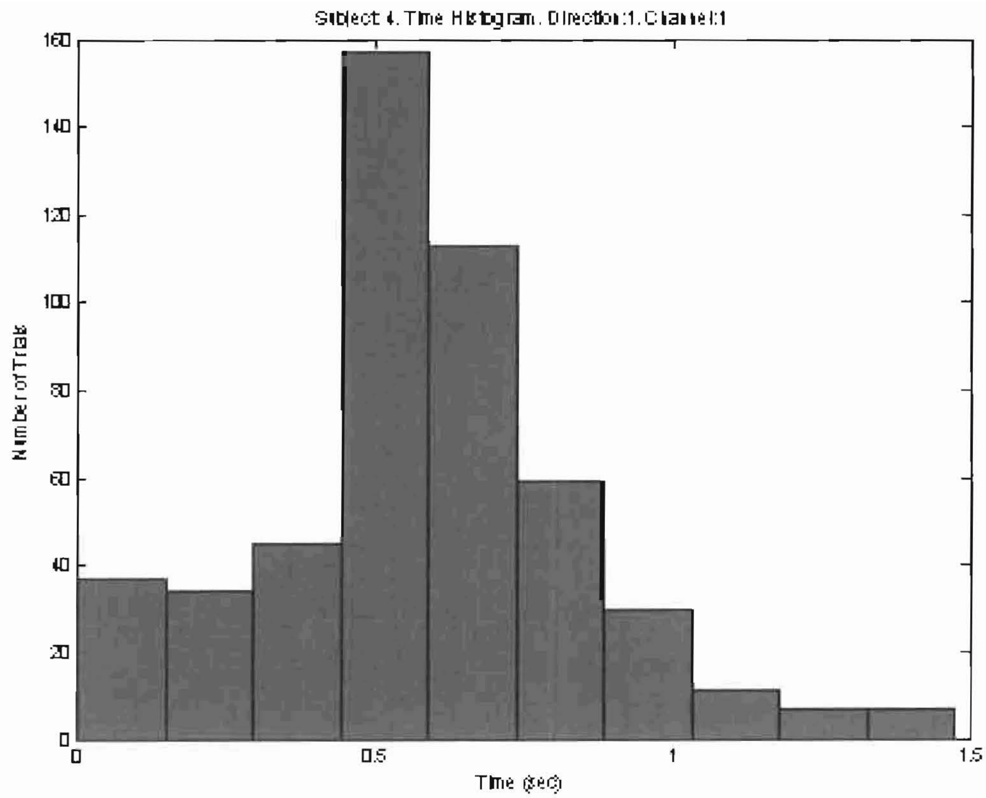

Subject 3. Time Histogram. Direction:1. Channel:2
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0.2
0.4
0.6
0.8
1
1.2
1.4

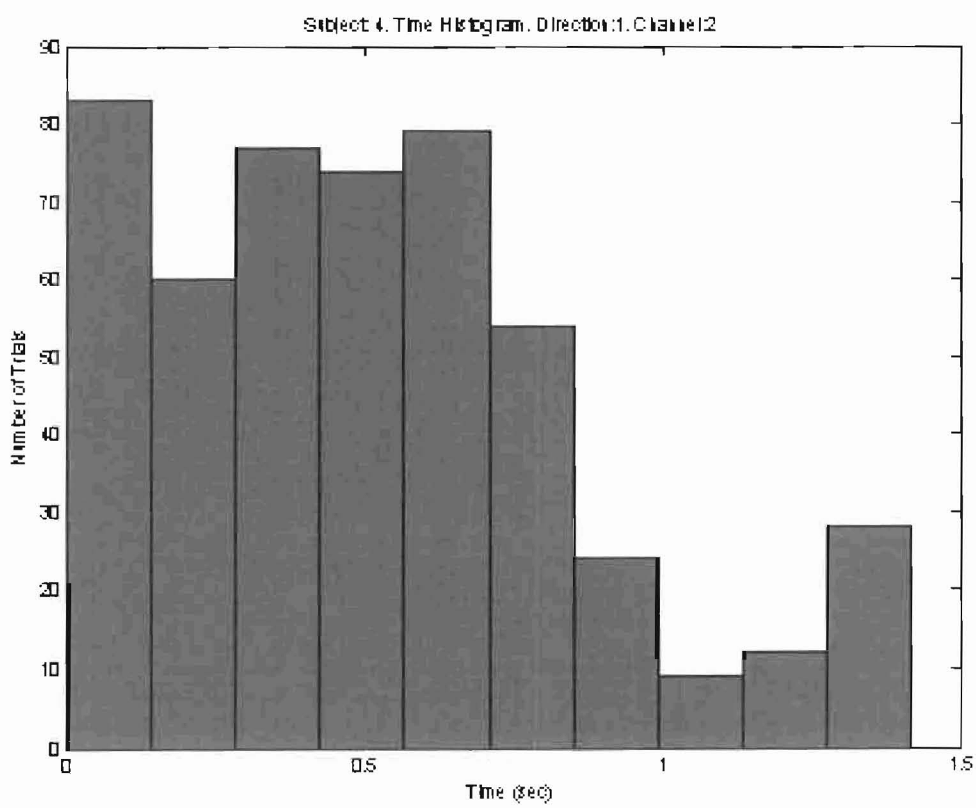

Subject 3. Time Histogram. Direction:1. Channel:3
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0.2
0.4
0.6
0.8
1
1.2
1.4

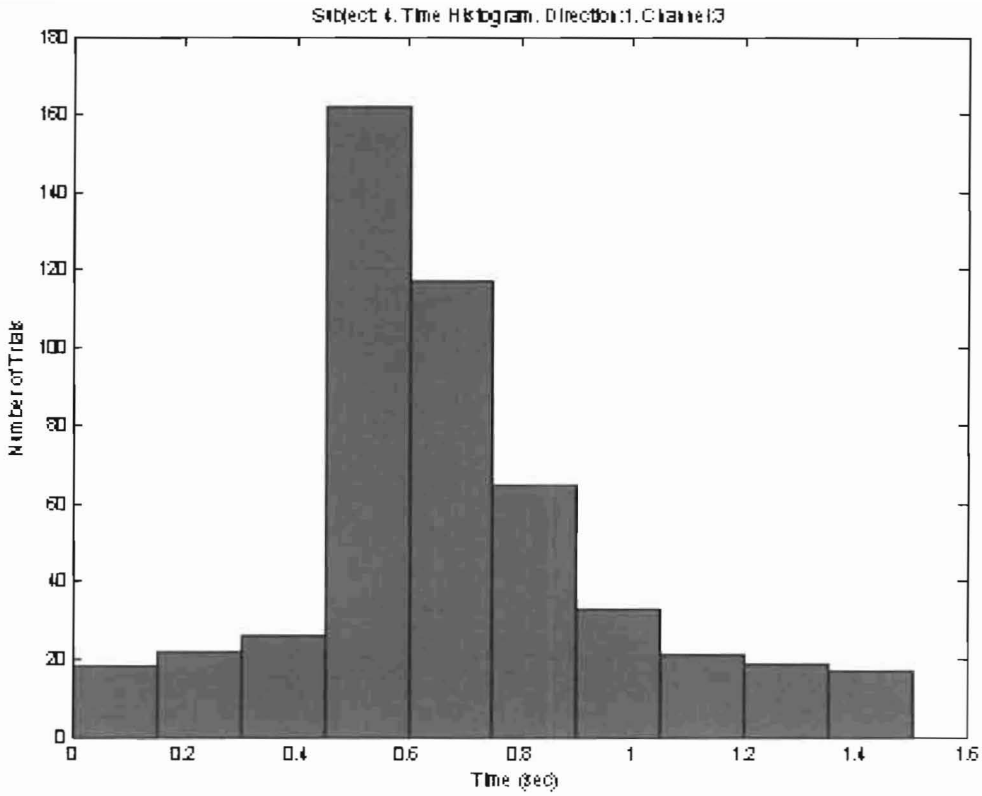

Subject 3. Time Histogram. Direction:2. Channel:1
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
0.5
1
1.5

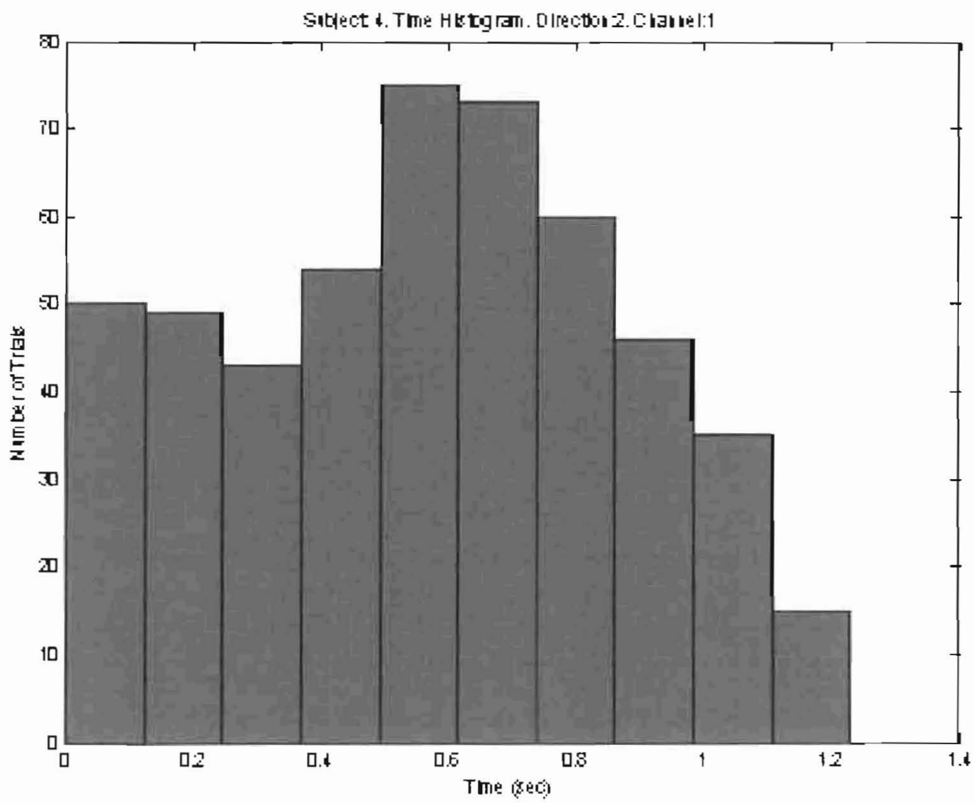

Subject 3. Time Histogram. Direction 2. Channel 2
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0.5
1
1.5

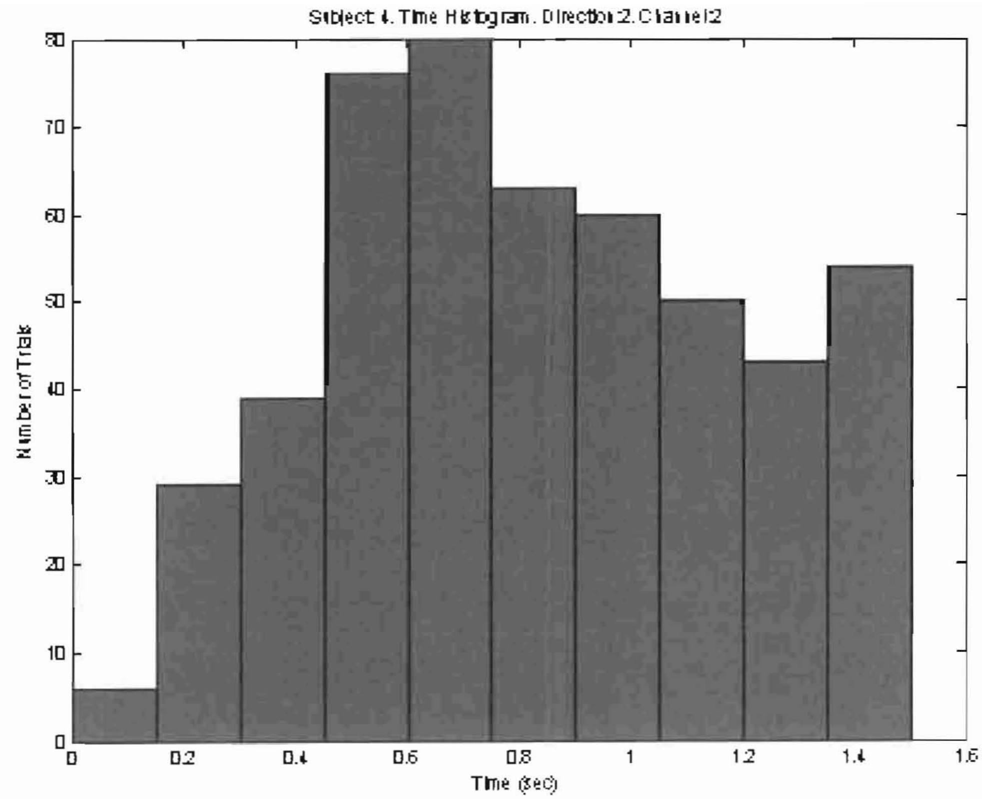

Subject 3. Time Histogram. Direction 2. Channel 3
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
0.2
0.4
0.6
0.8
1
1.2
1.4

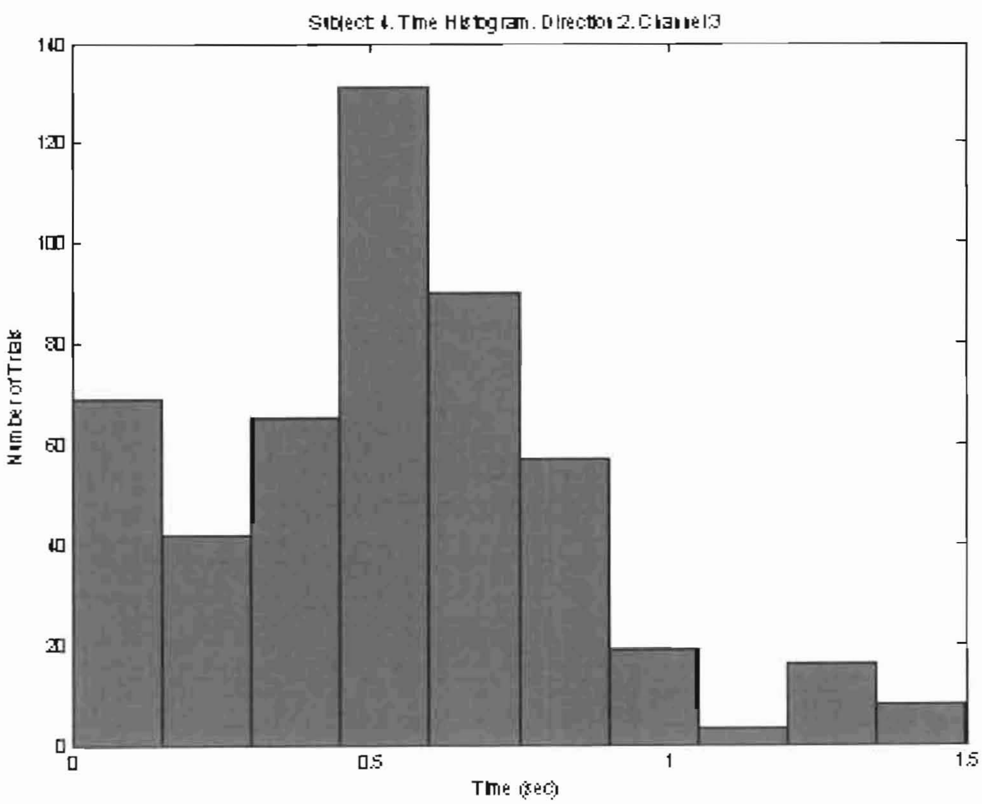

Subject 4. Time Histogram. Direction:1. Channel:1
Number of Trials
Time (sec)

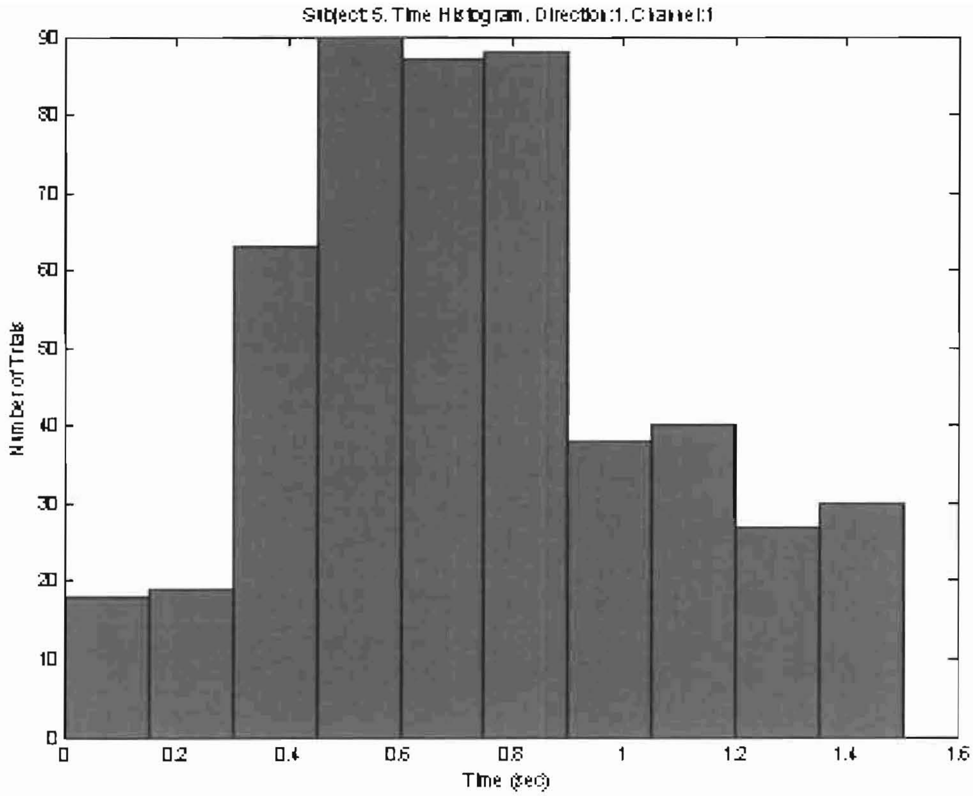

Subject 4. Time Histogram. Direction:1. Channel:2
Number of Trials
Time (sec)

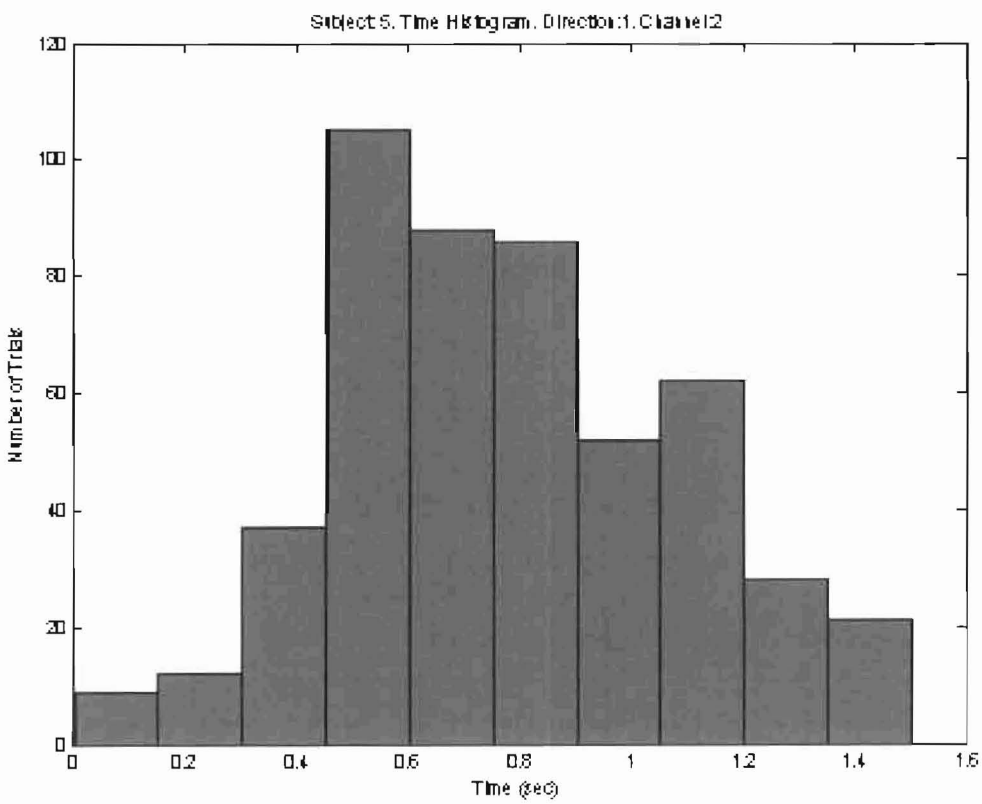

Subject 4. Time Histogram. Direction:1. Channel:3
Number of Trials
Time (sec)
0
20
40
60
80
100
120
140
160
180
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

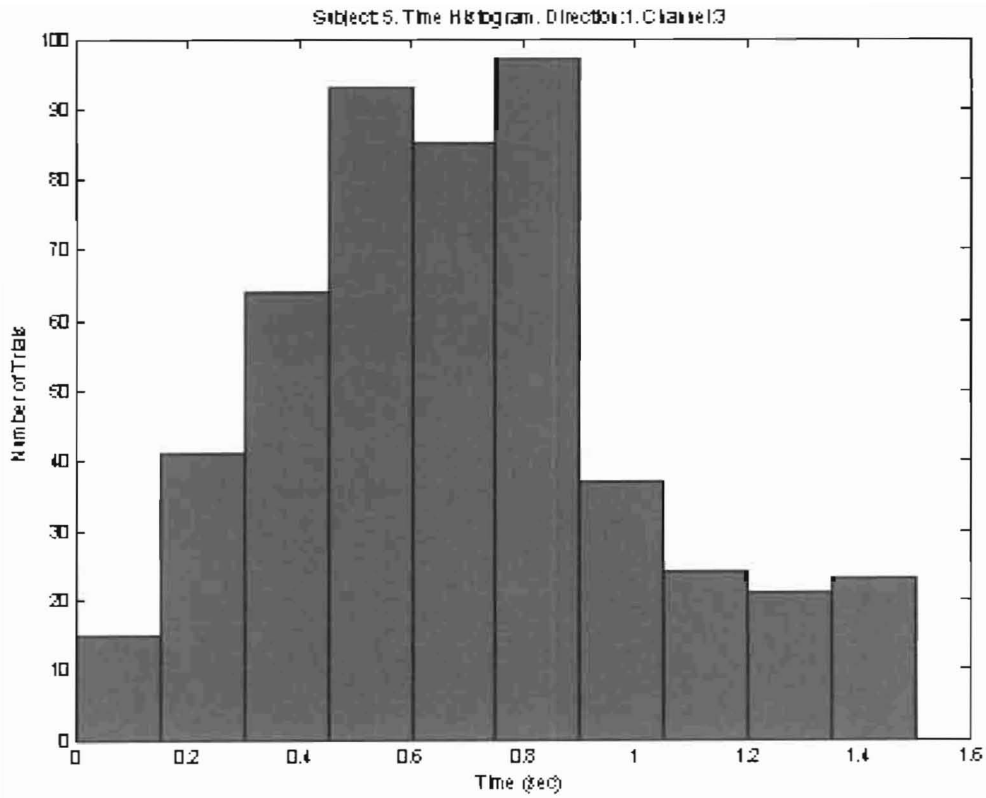

Subject 4. Time Histogram. Direction:2. Channel:1
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
0.2
0.4
0.6
0.8
1
1.2
1.4

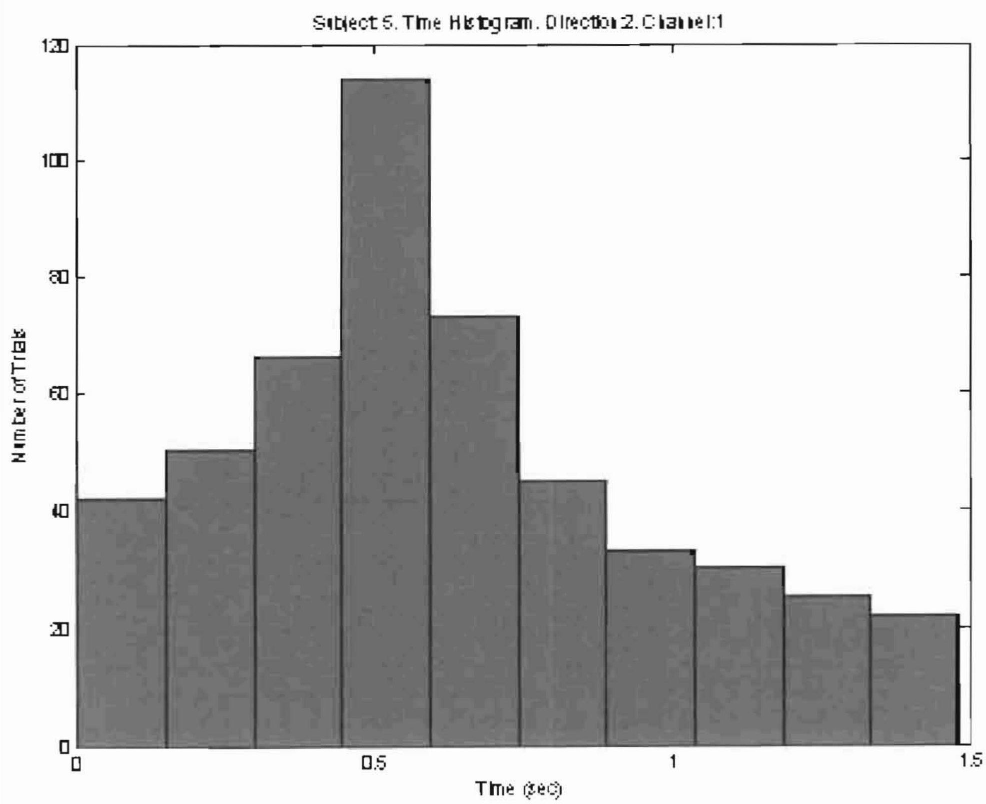

Subject 4. Time Histogram. Direction 2. Channel 2
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

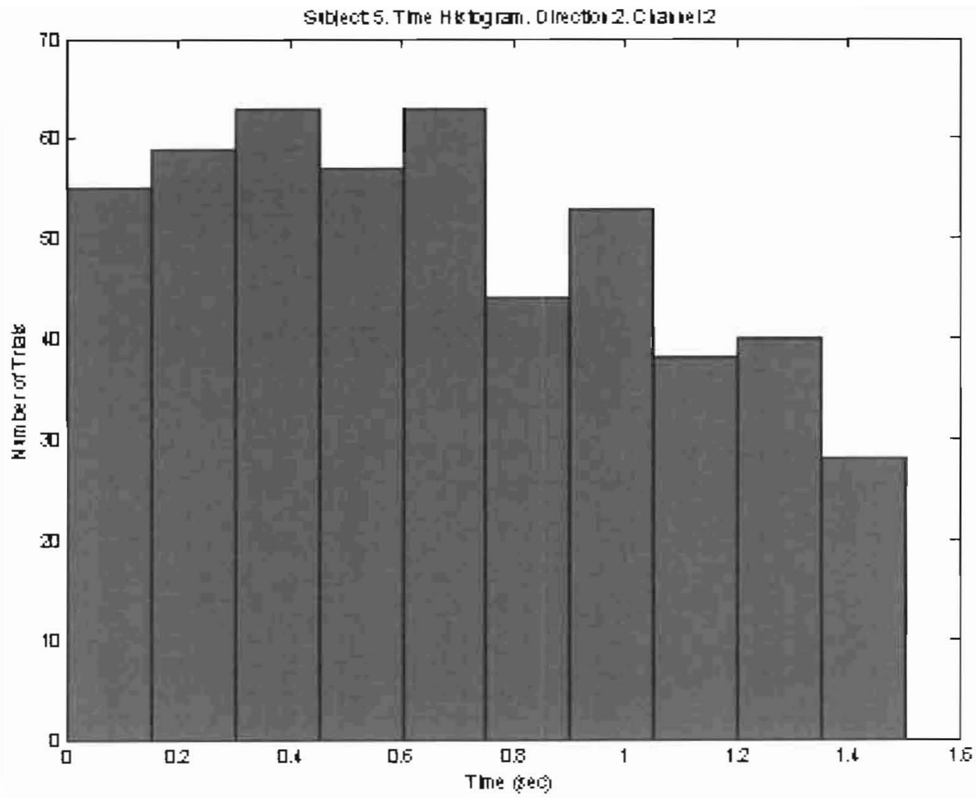

Subject 4. Time Histogram. Direction 2. Channel 3
Number of Trials
Time (sec)
0
20
40
60
80
100
120
140
0
0.5
1
1.5

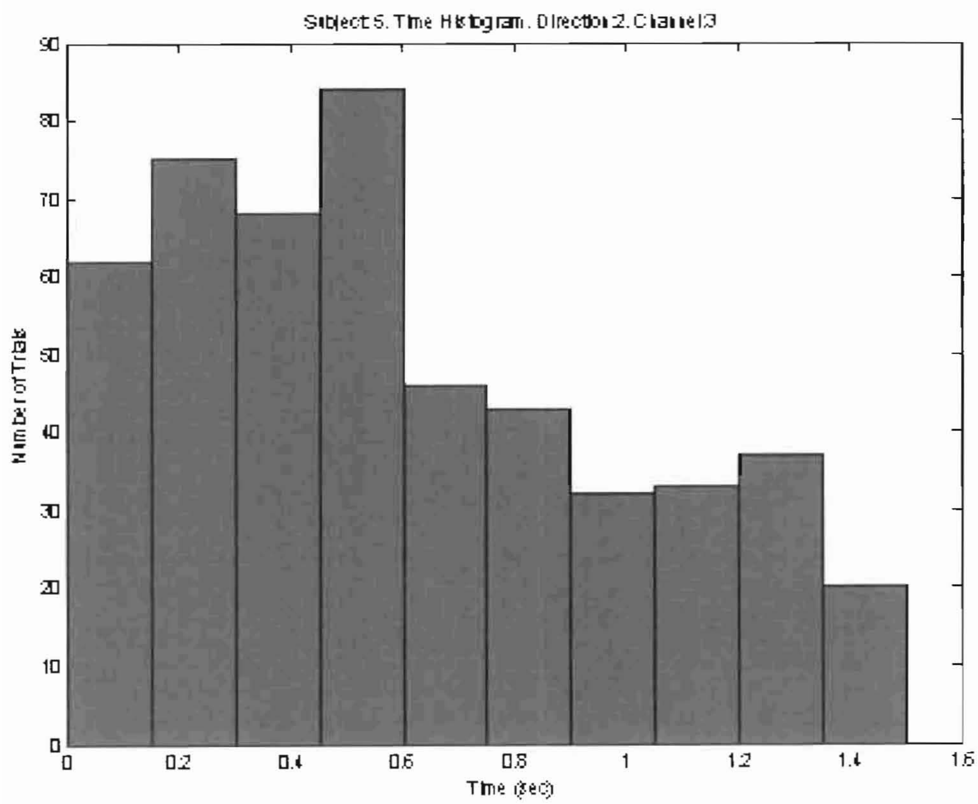

Subject 5. Time Histogram. Direction:1. Channel:1
Number of Trials
Time (sec)


Subject 5. Time Histogram. Direction:1. Channel:2
Number of Trials
Time (sec)

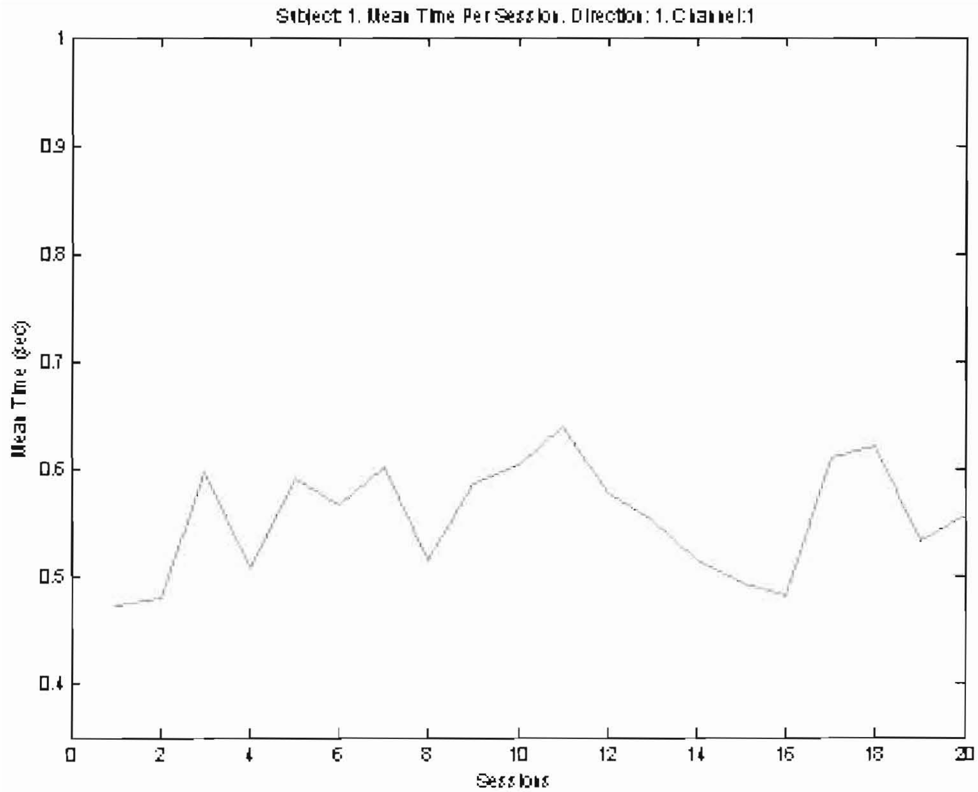

Subject 5. Time Histogram. Direction:1. Channel:3
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
90
100
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6


Subject 5. Time Histogram. Direction:2. Channel:1
Number of Trials
Time (sec)
0
20
40
60
80
100
120
0.5
1
1.5

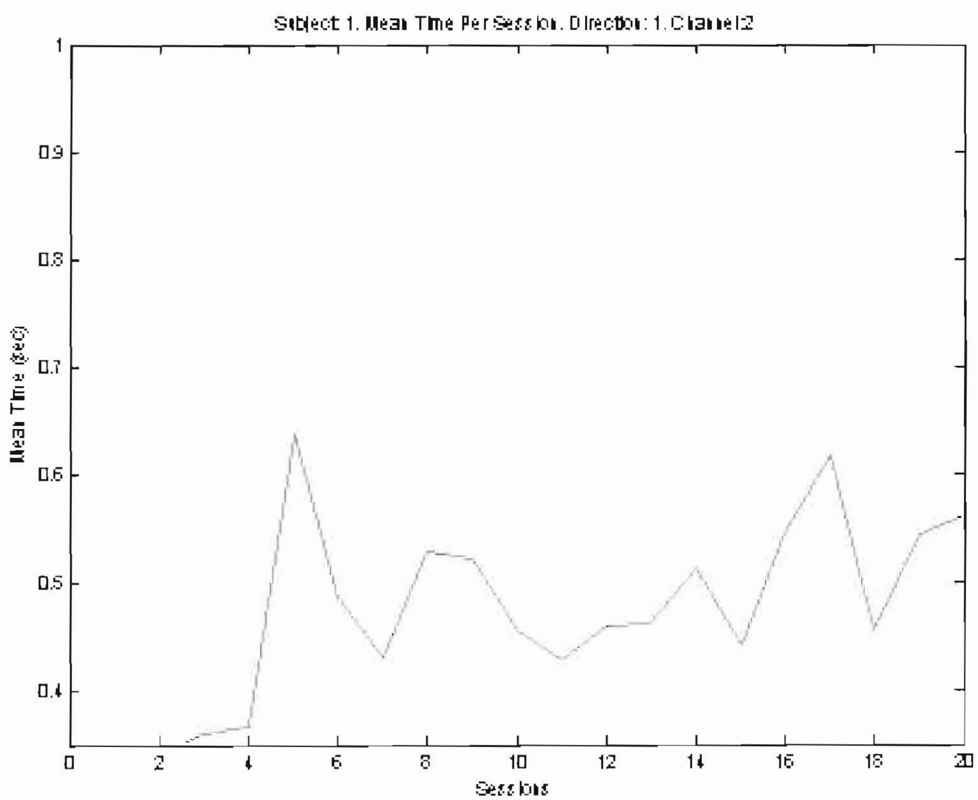

Subject 5. Time Histogram. Direction 2. Channel 2
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6


Subject 5. Time Histogram. Direction 2. Channel 3
Number of Trials
Time (sec)
0
10
20
30
40
50
60
70
80
90
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

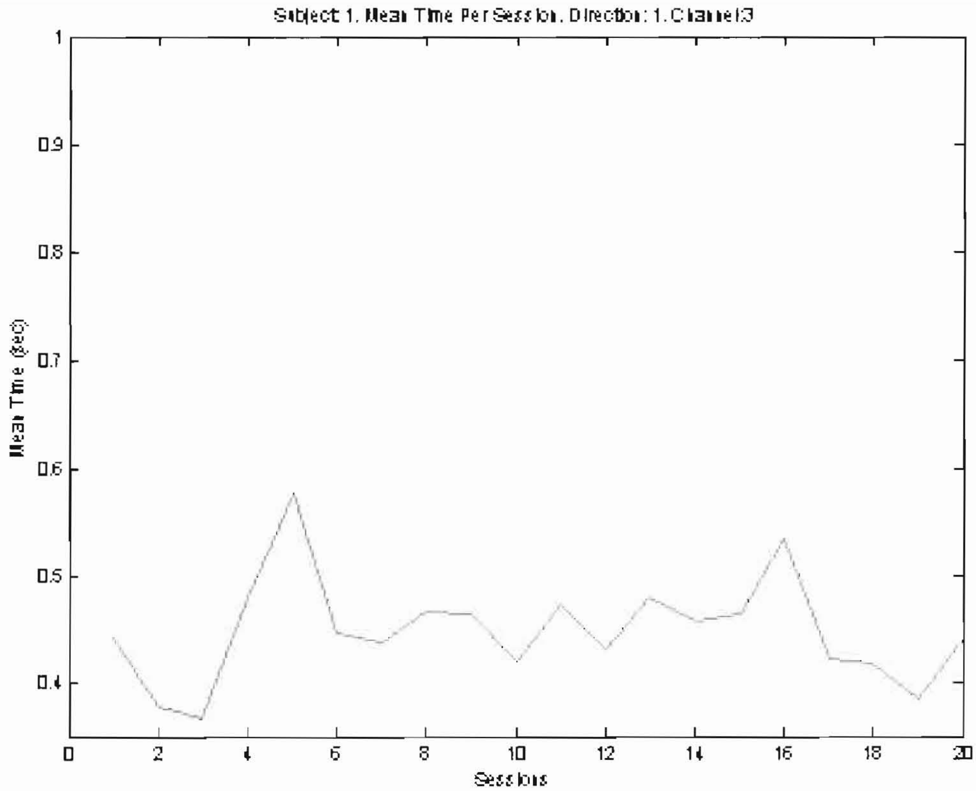
APPENDIX 3: MEAN REACTION TIME PER SESSION RESULTS

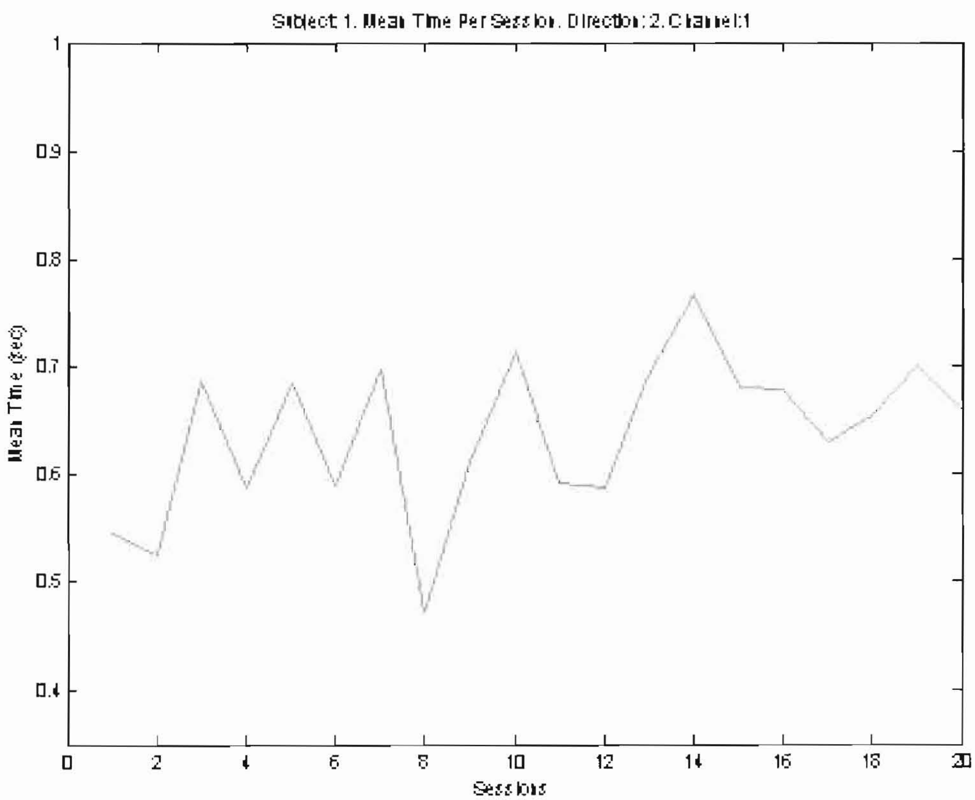


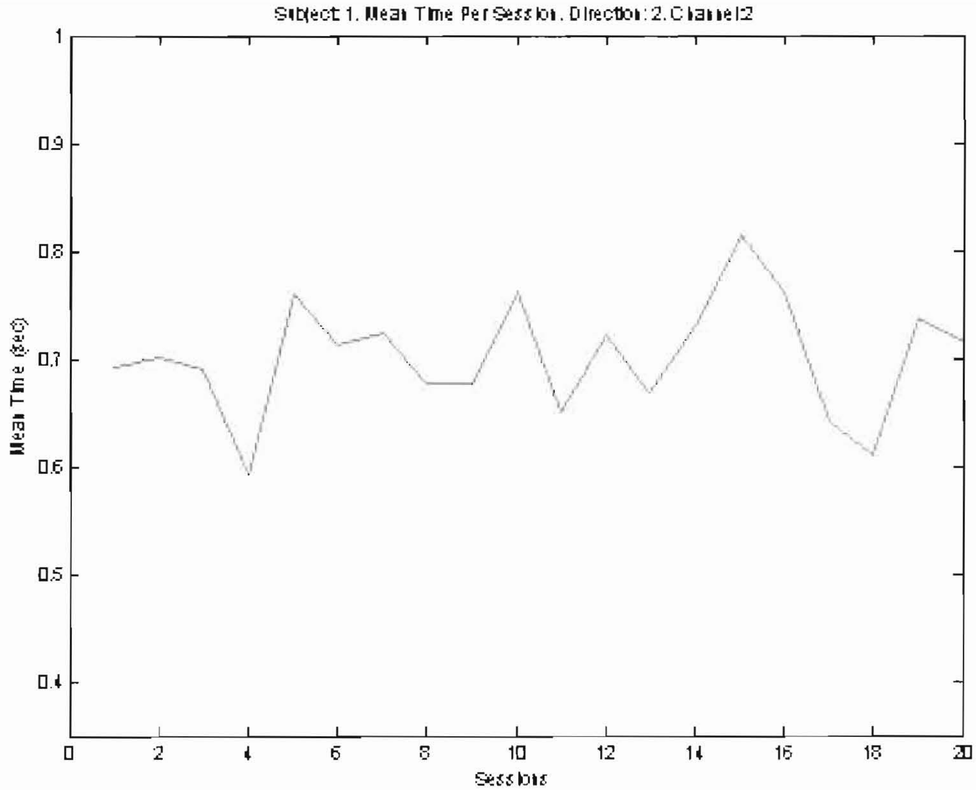
Subject 1. Mean Time Per Session. Direction: 1. Channel:1
Mean Time (sec)
Sessions

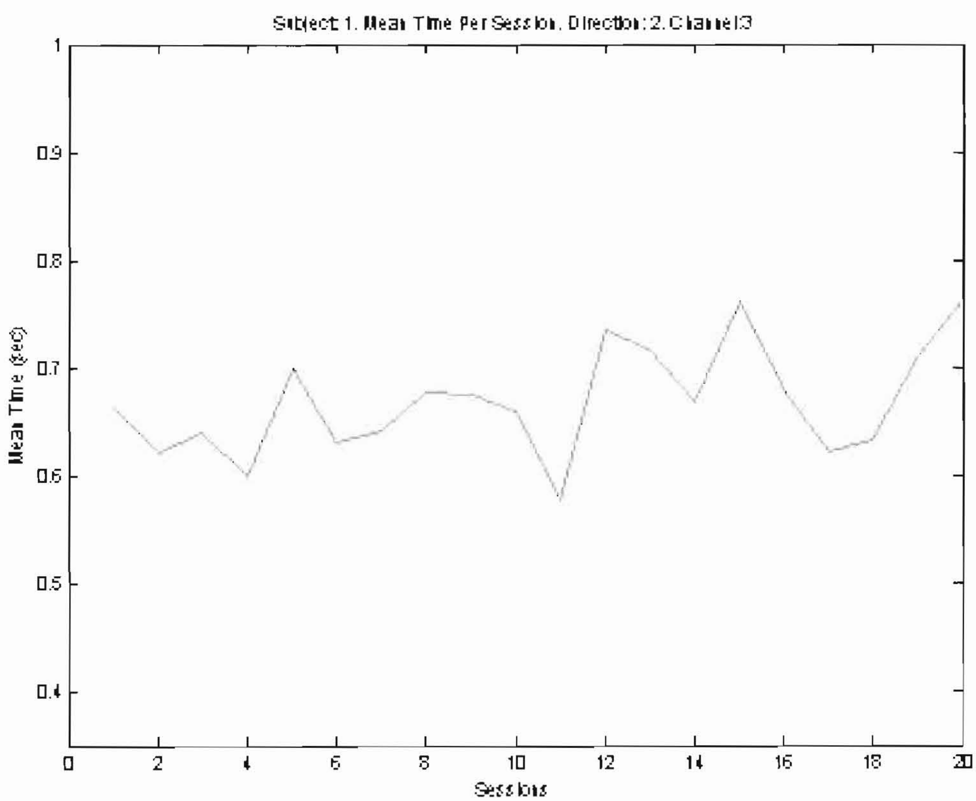


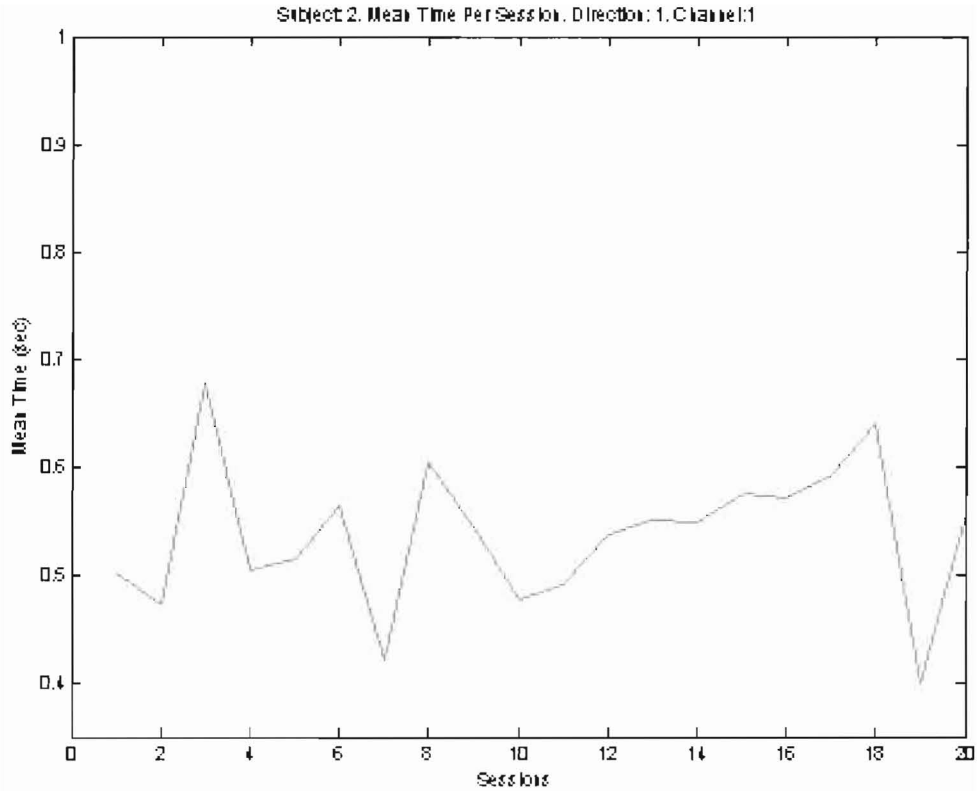
Subject 1. Mean Time Per Session. Direction: 1. Channel:2
Mean Time (sec)
Sessions

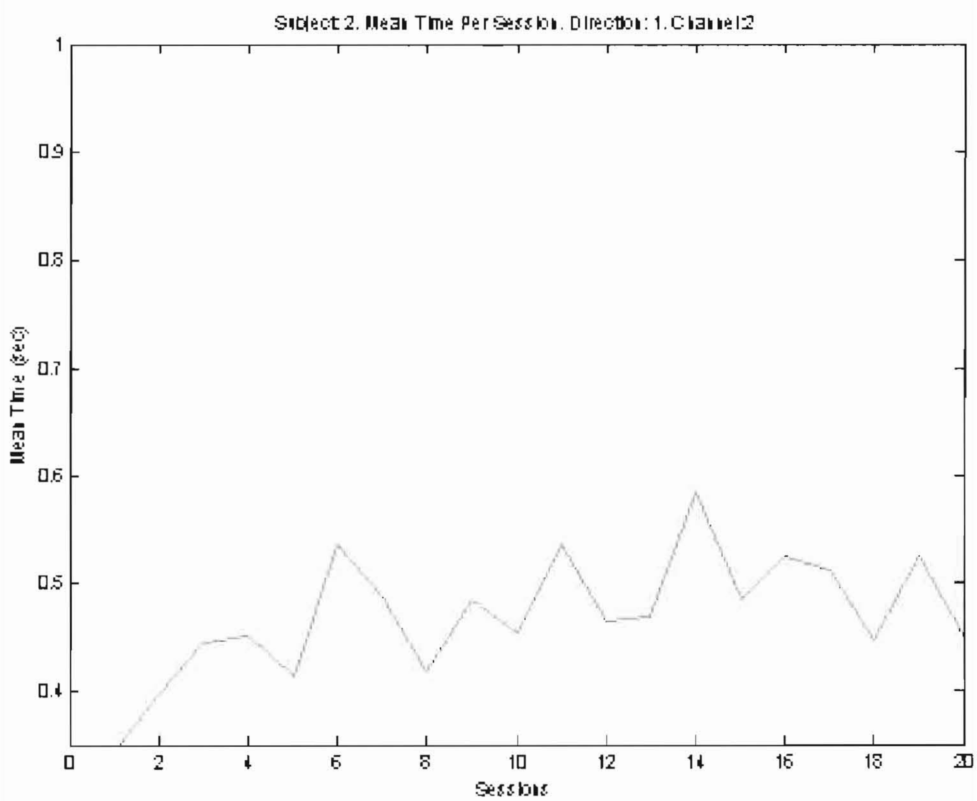

Subject 1. Mean Time Per Session. Direction: 1. Channel:3
Mean Time (sec)
Sessions
1
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
20

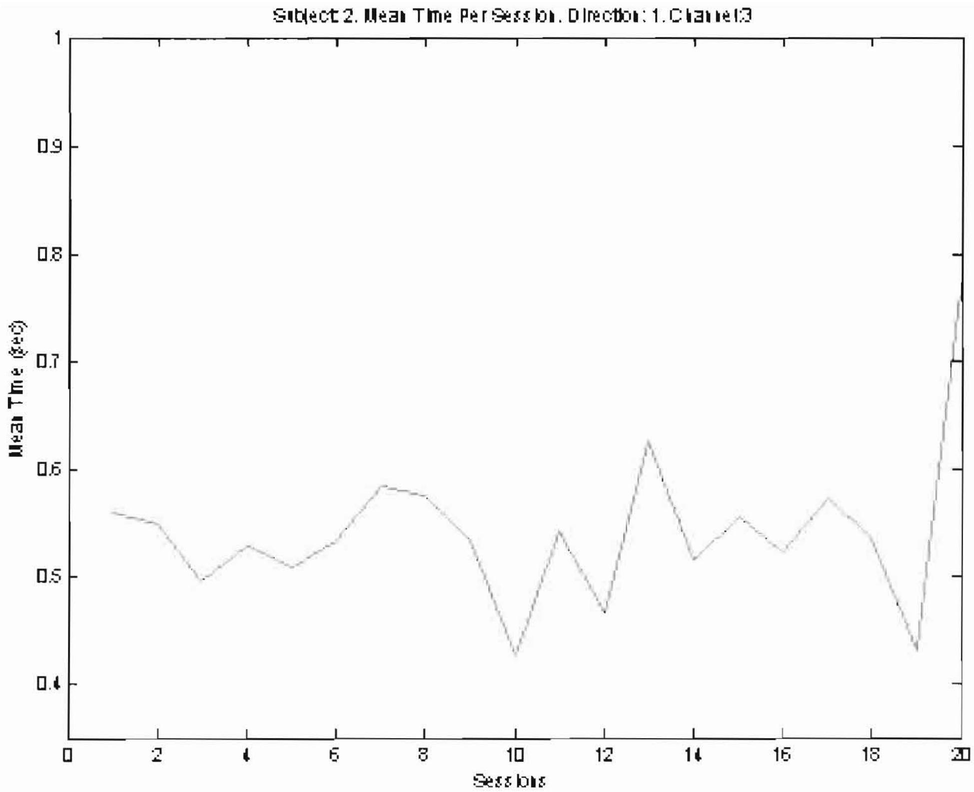

Subject 1. Mean Time Per Session. Direction: 2. Channel:1
Mean Time (sec)
Sessions
1
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
20

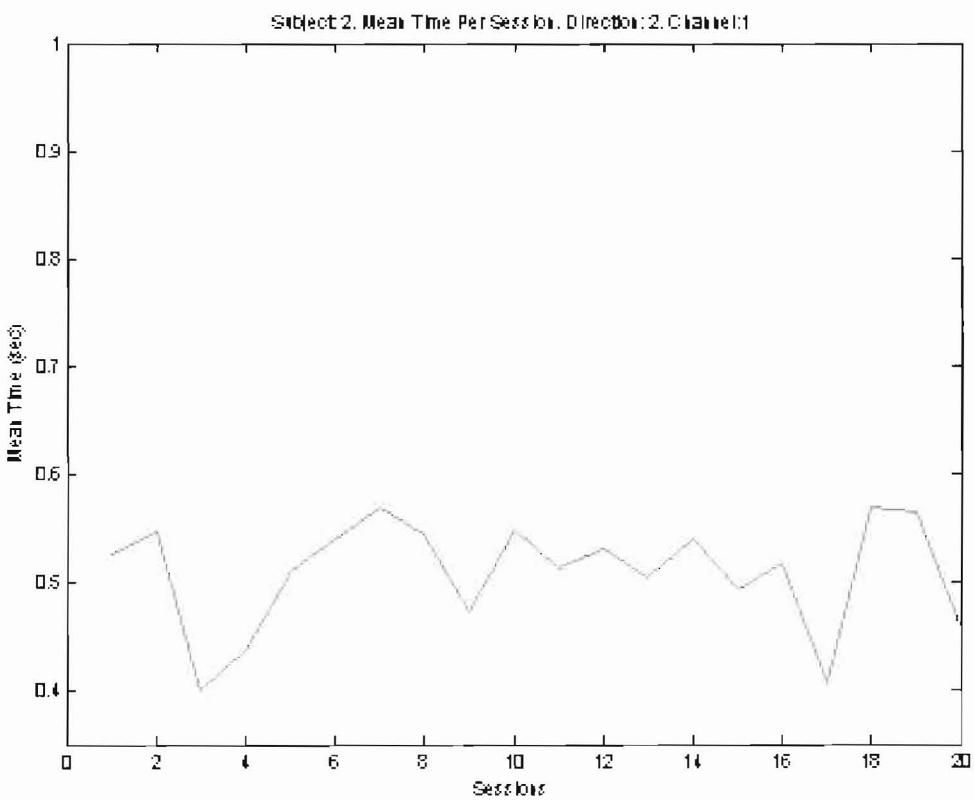

Subject 1. Mean Time Per Session. Direction: 2. Channel 2
Mean Time (sec)
1
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
20
Sessions


Subject 1. Mean Time Per Session. Direction: 2. Channel 3
Mean Time (sec)
1
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
20
Sessions


Subject 2. Mean Time Per Session. Direction: 1. Channel:1
Mean Time (sec)
Sessions


Subject 2. Mean Time Per Session. Direction: 1. Channel:2
Mean Time (sec)
Sessions


Subject 2. Mean Time Per Session. Direction: 1. Channel:3
Mean Time (sec)
Sessions
1
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
20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Mean Time (sec)
Sessions
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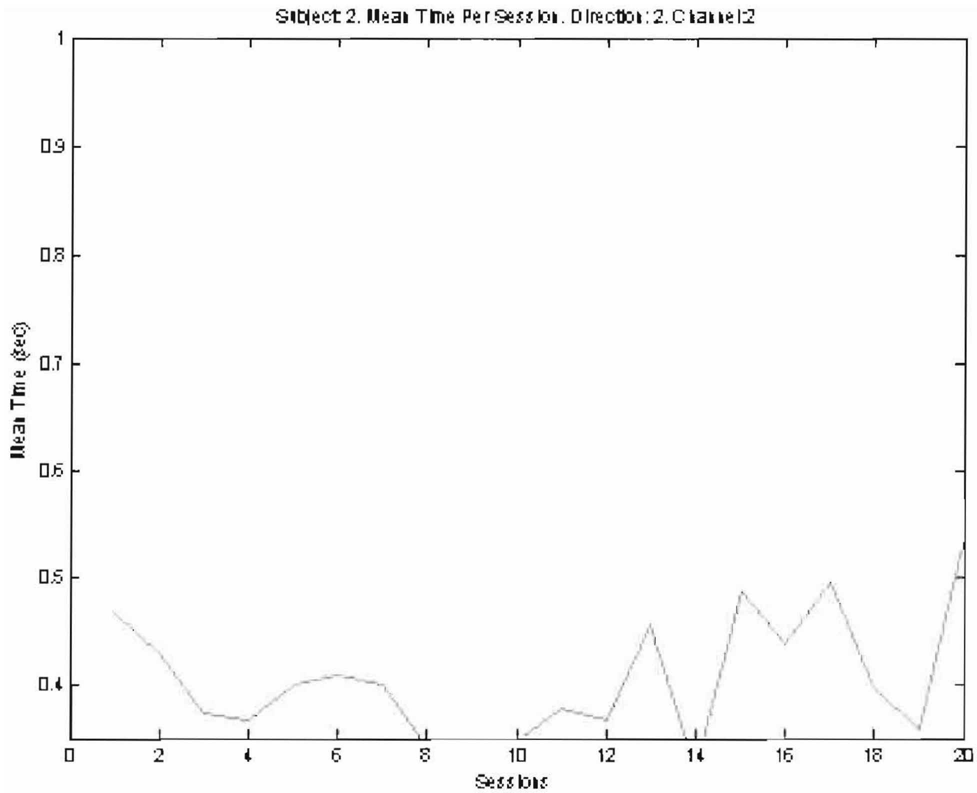
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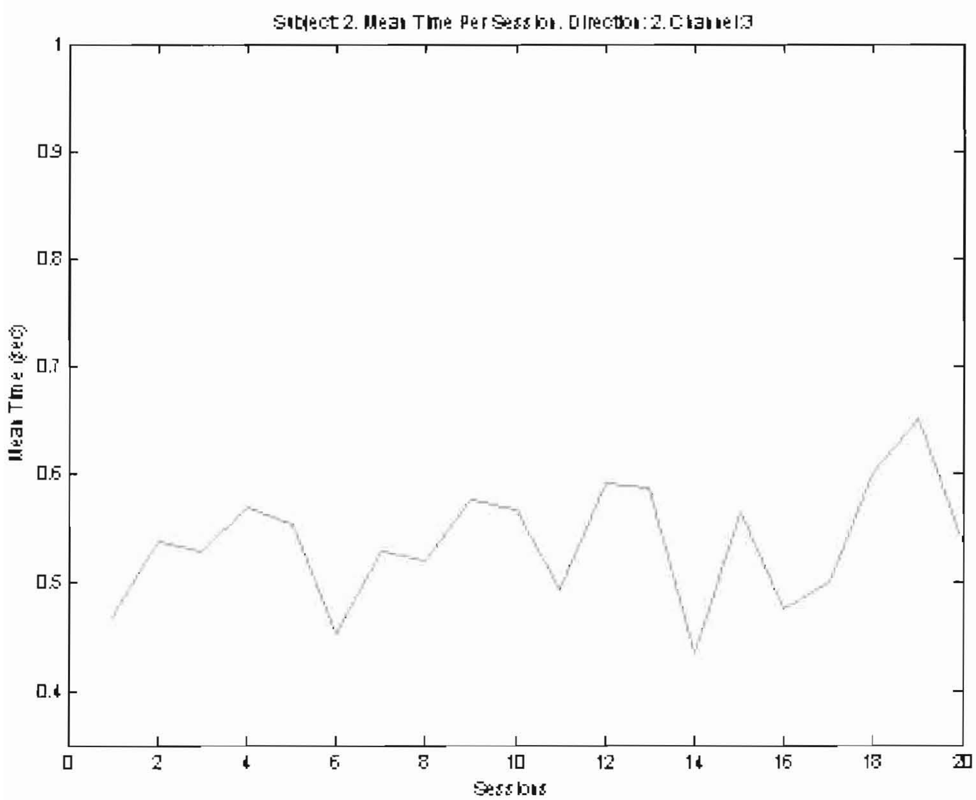
Mean Time (sec)
Sessions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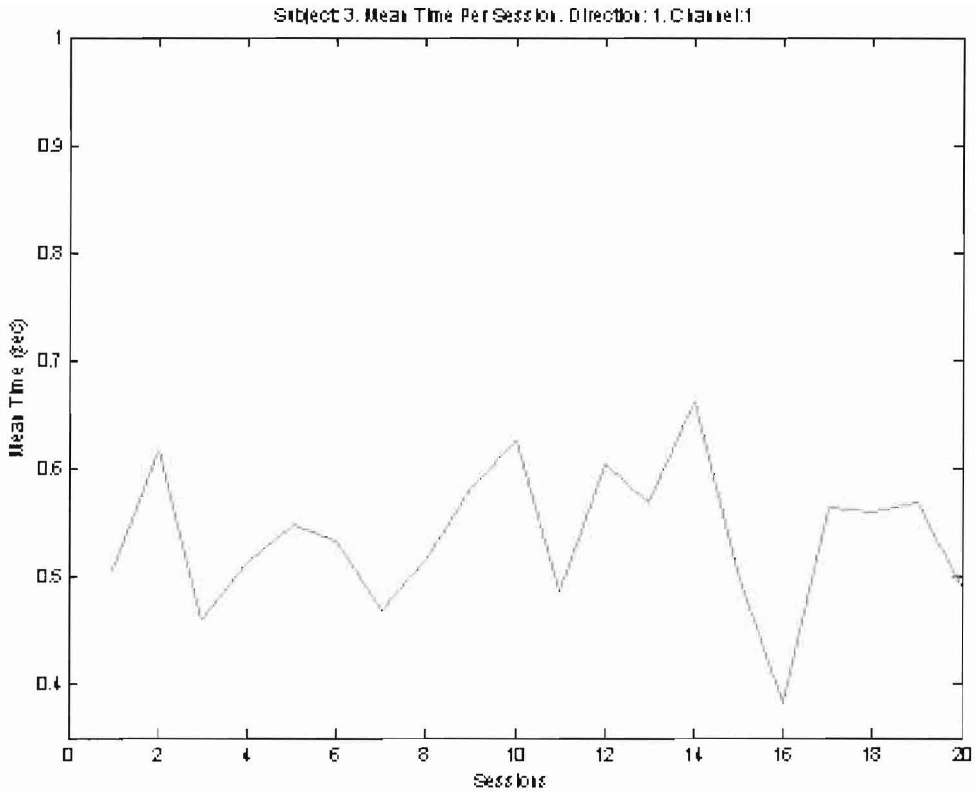
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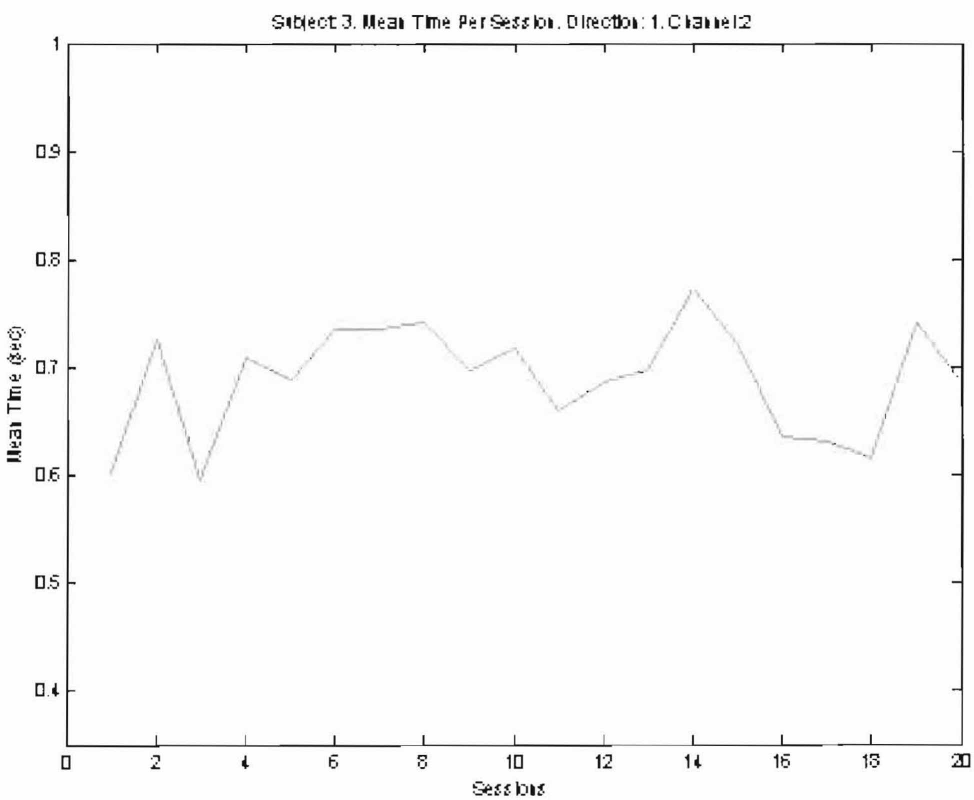
Mean Time (sec)
Sessions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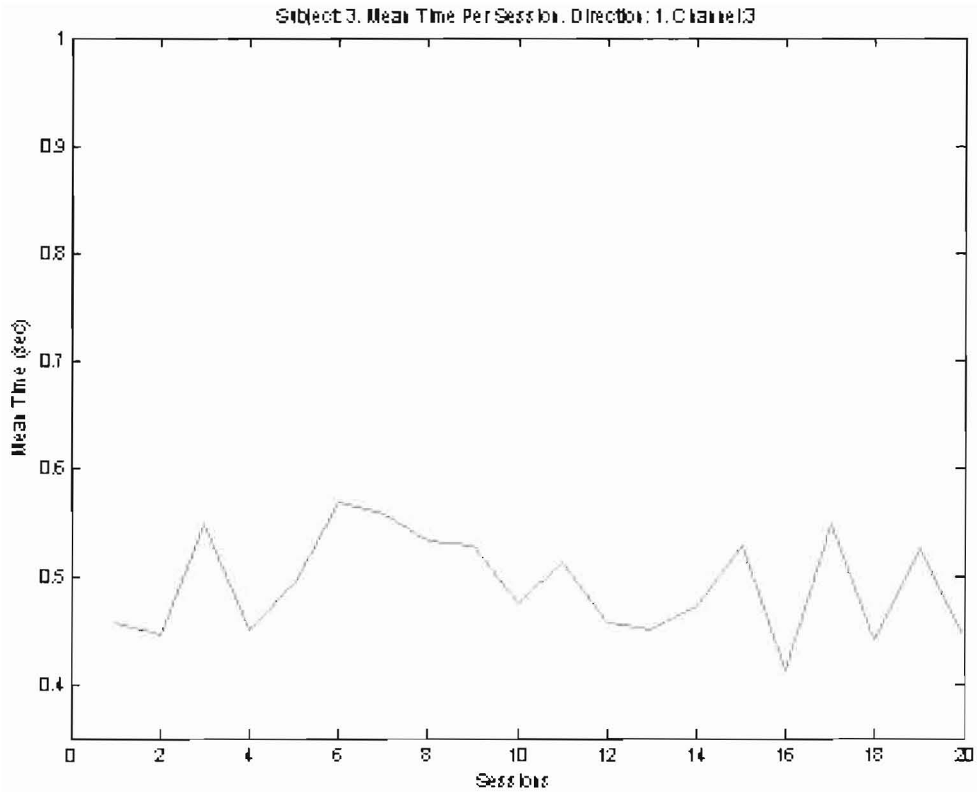
Mean Time (sec)
Sessions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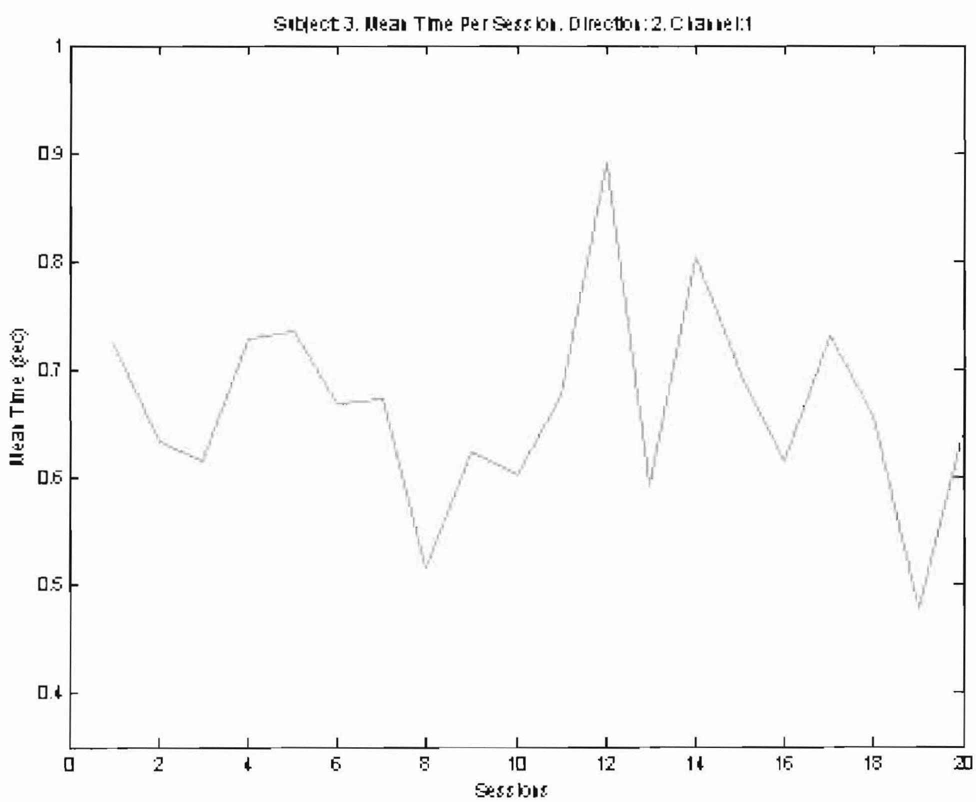
Mean Time (sec)
Sessions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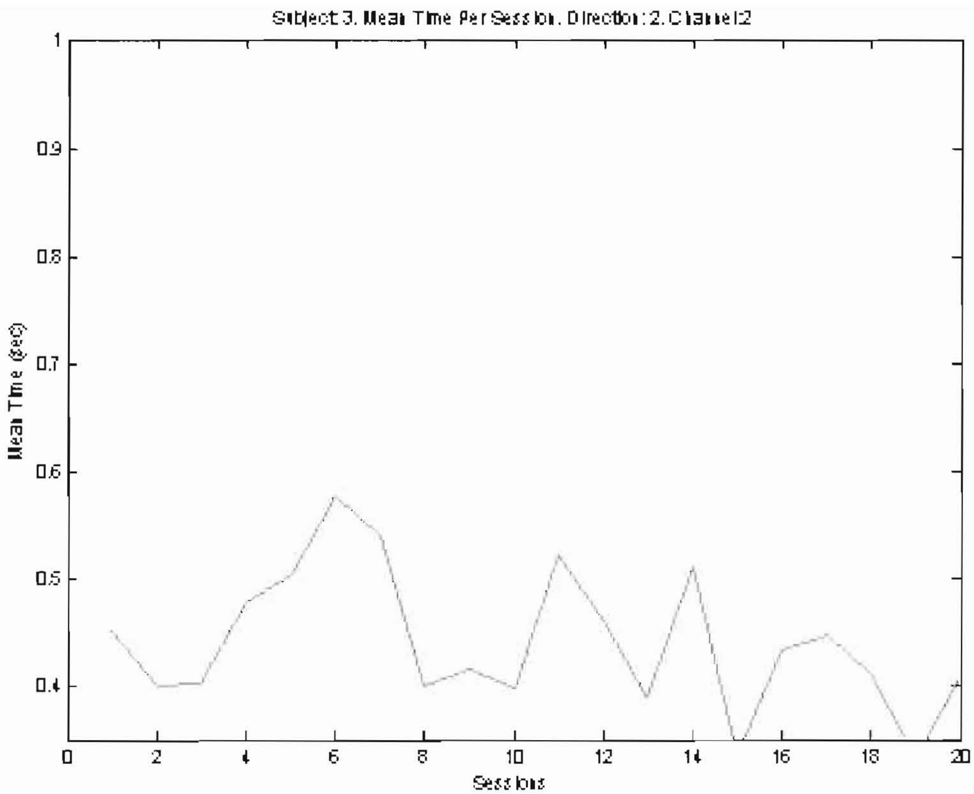
Mean Time (sec)
Sessions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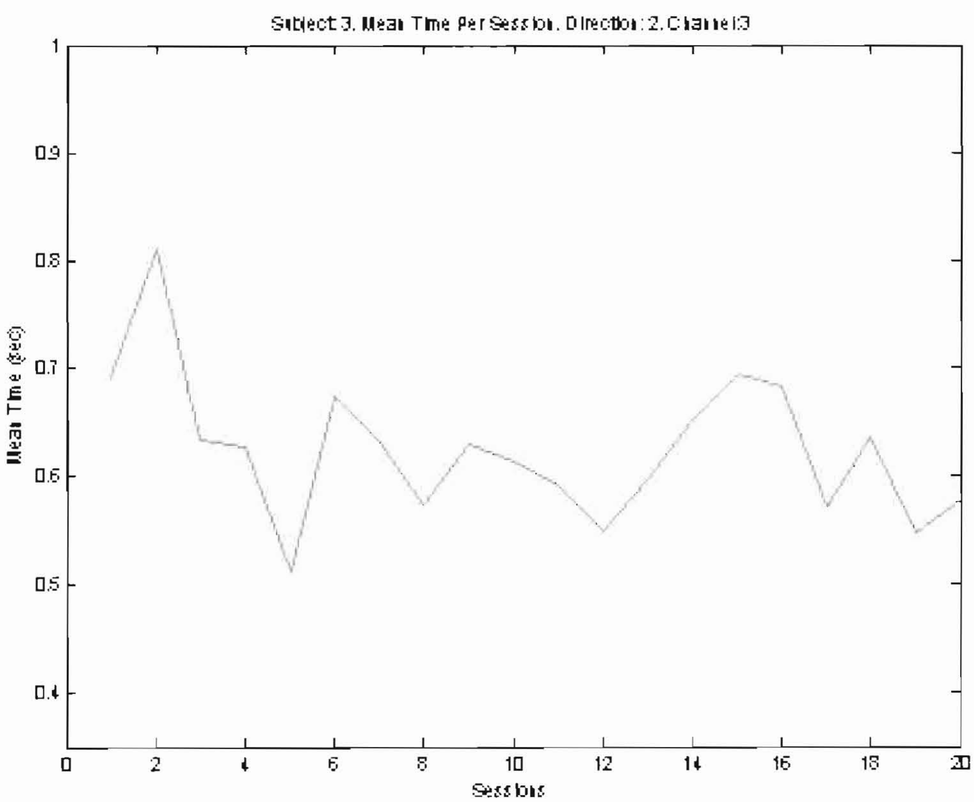
Sessions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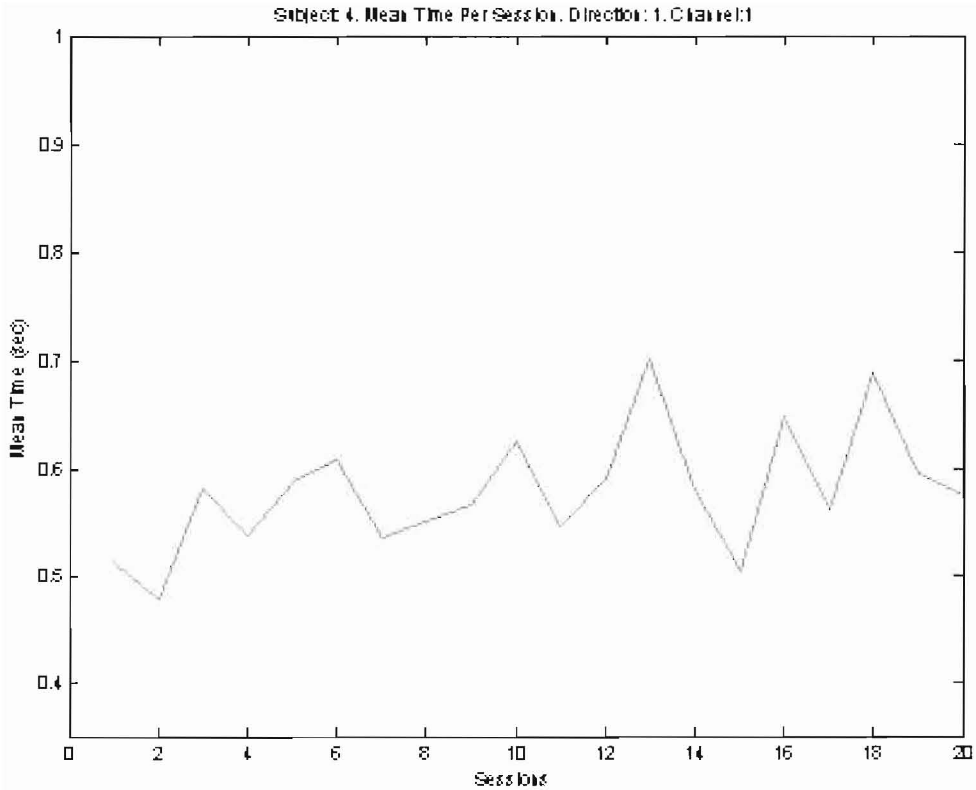
Mean Time (sec)
Sessions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Mean Time (sec)
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0.6
0.5
0.4
0
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6
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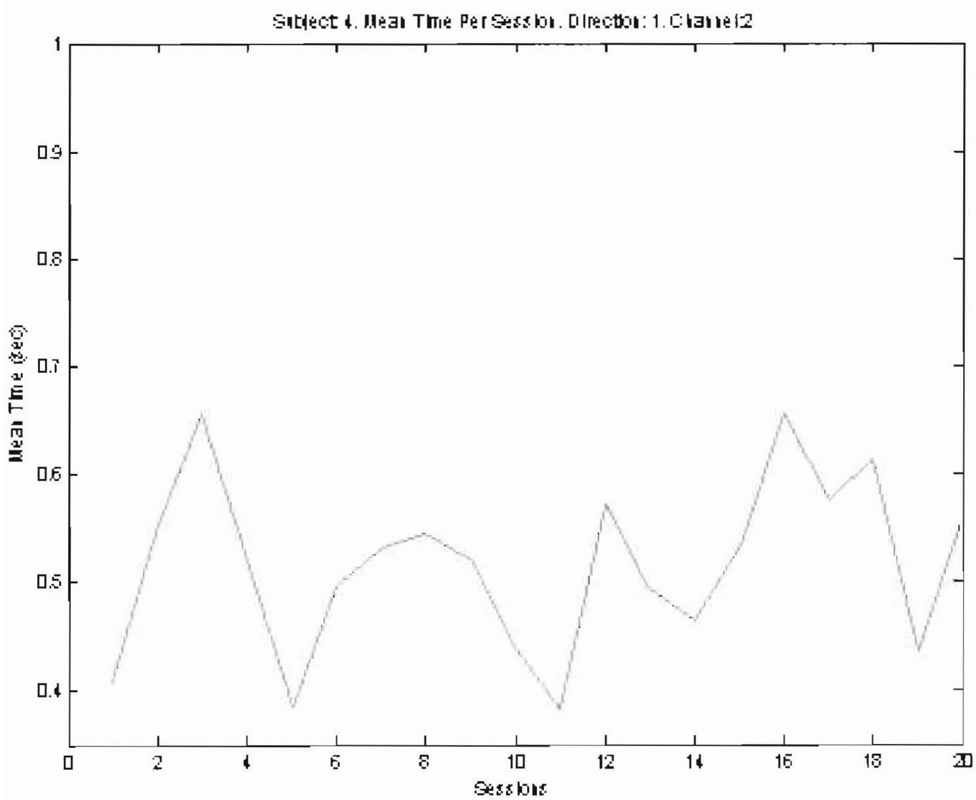
Subject 4. Mean Time Per Session. Direction: 1. Channel:2
Mean Time (sec)
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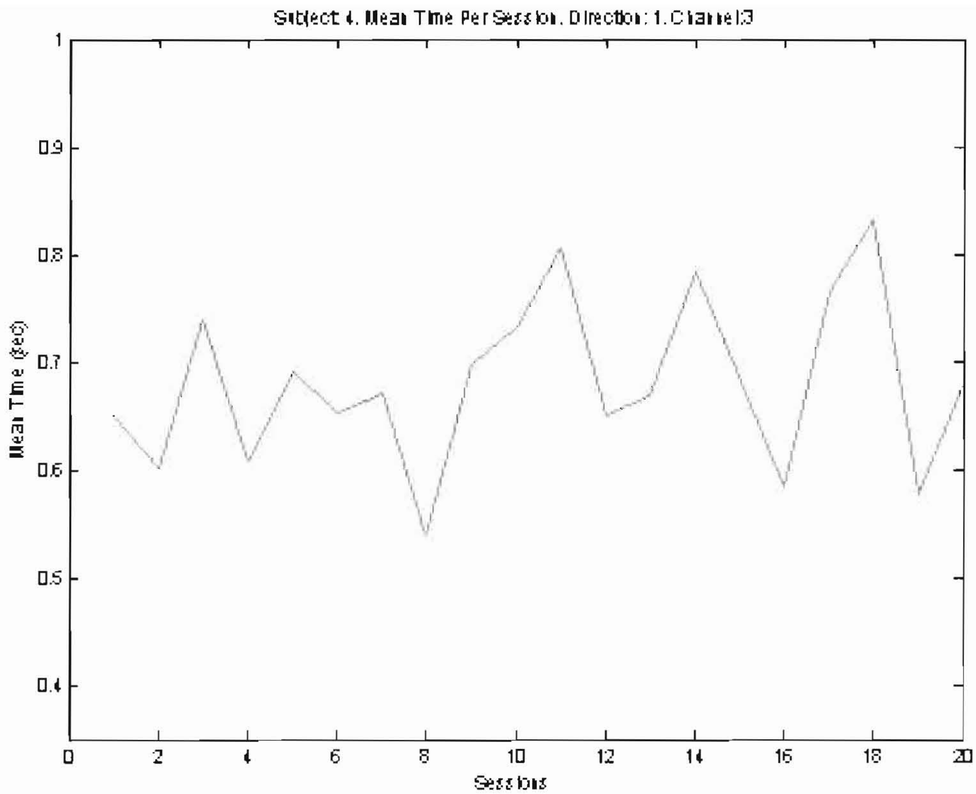
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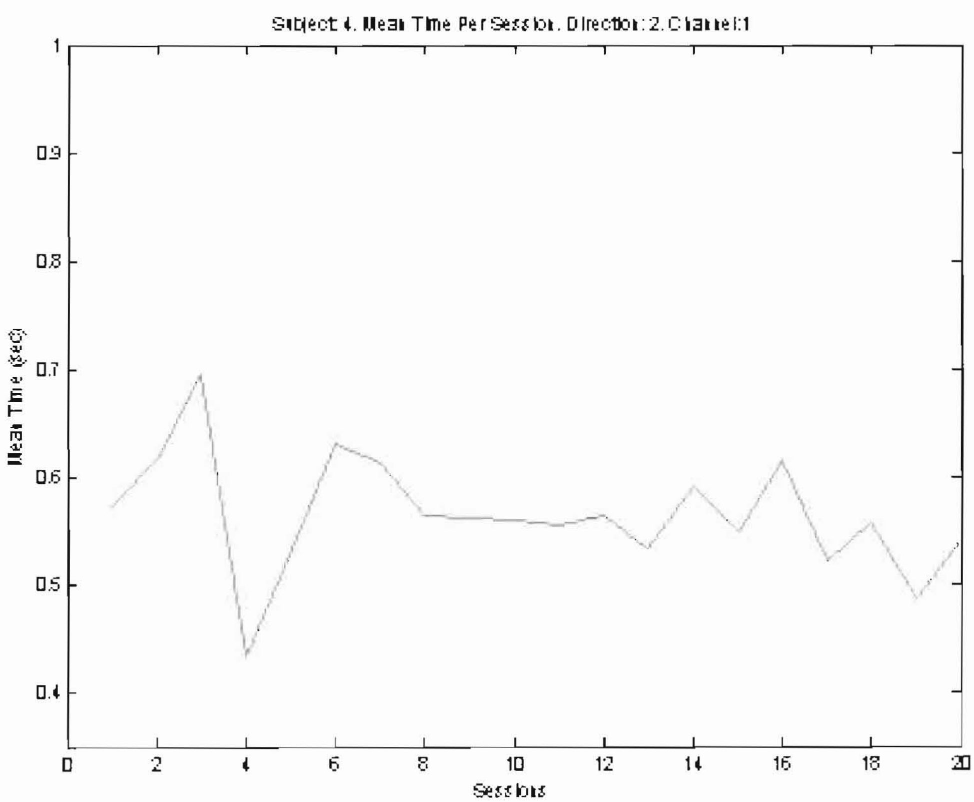
Mean Time (sec)
Sessions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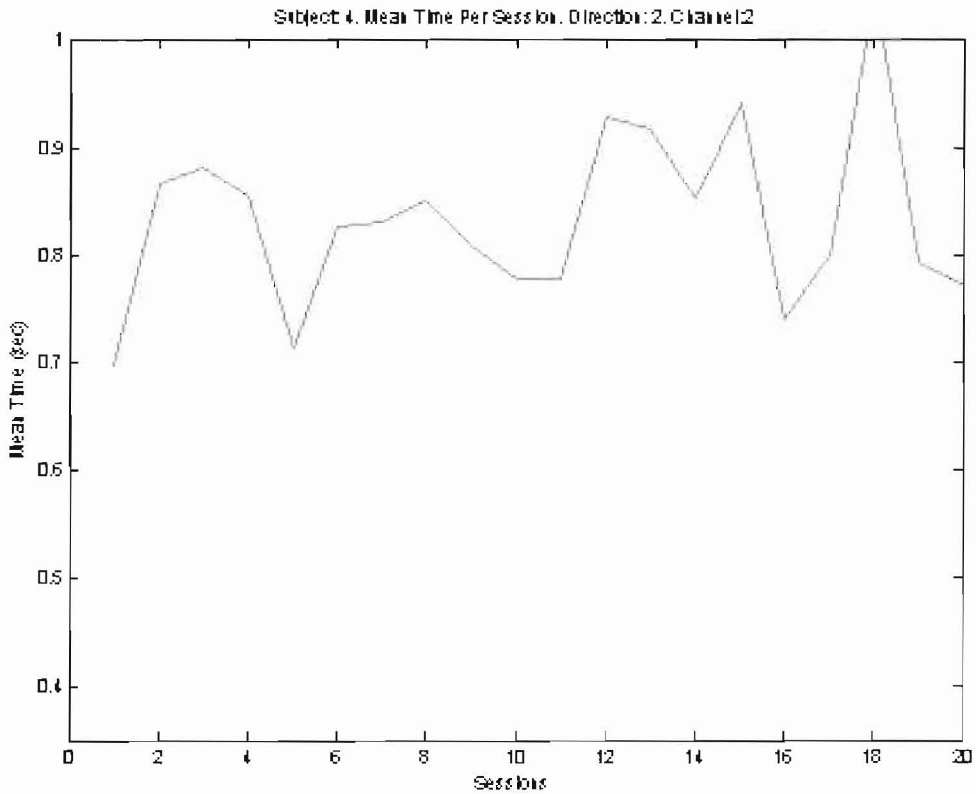
Mean Time (sec)
Sessions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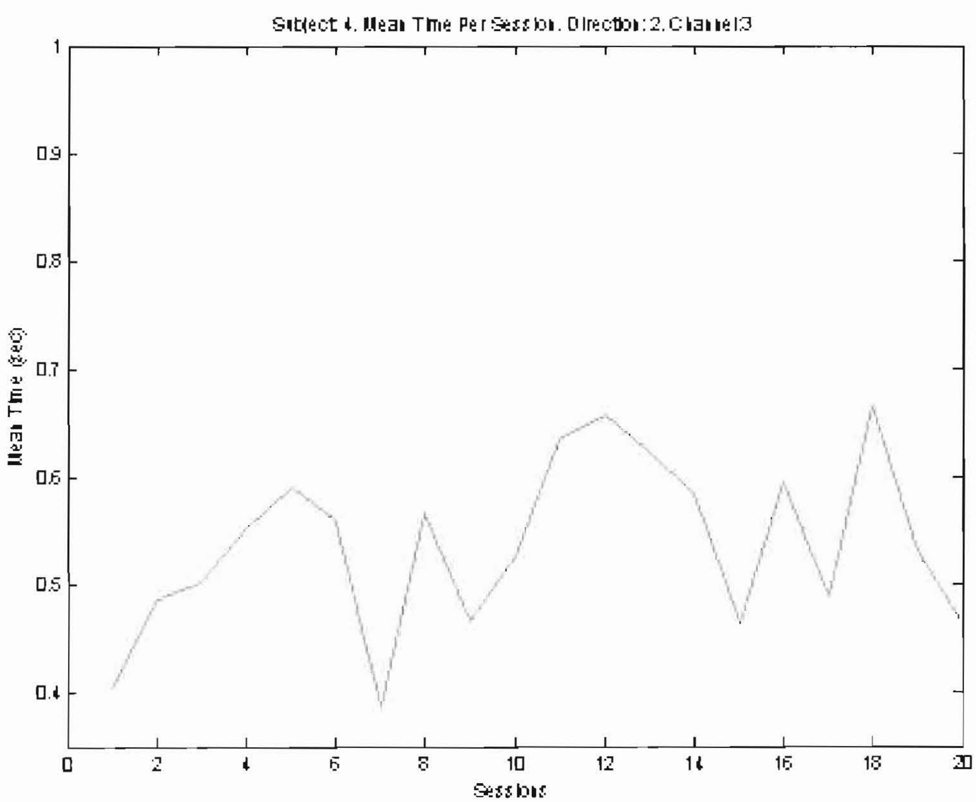
Mean Time (sec)
Sessions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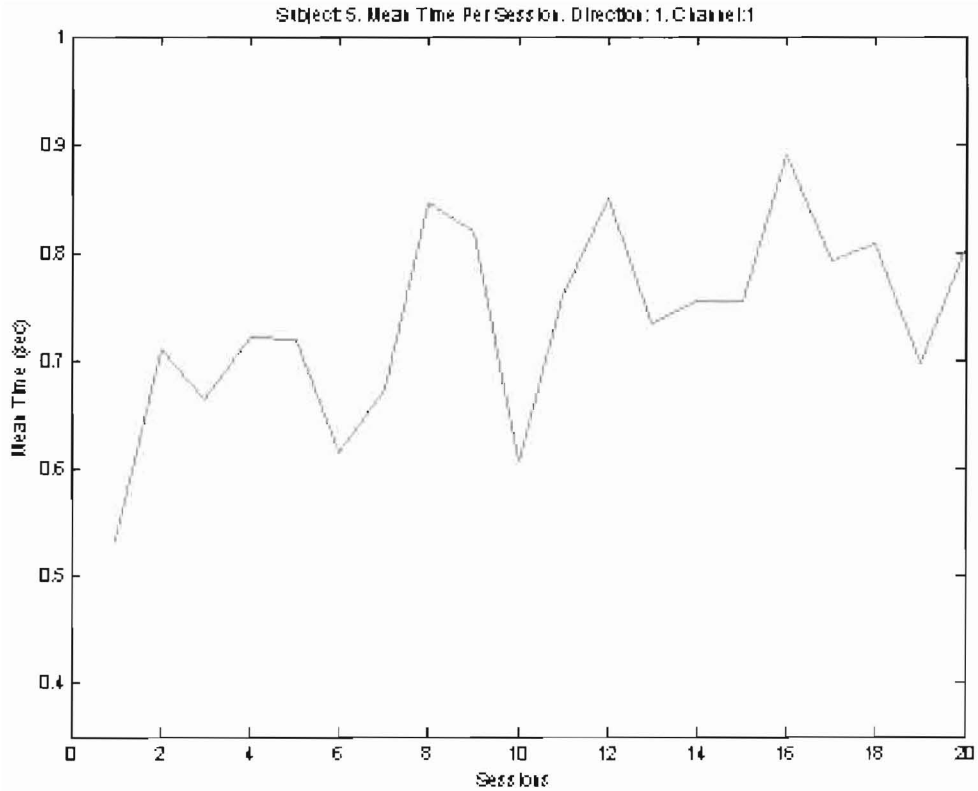
Mean Time (sec)
Sessions


Subject 5. Mean Time Per Session. Direction: 1. Channel:1
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Sessions
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0.6
0.5
0.4
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6
8
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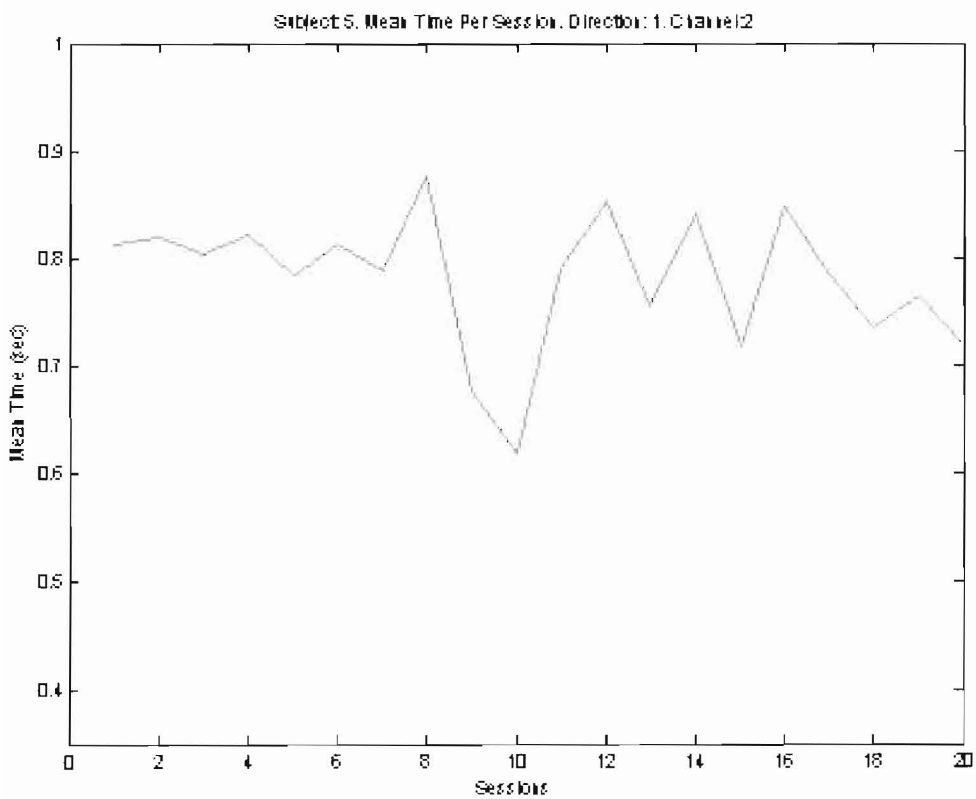
Subject 5. Mean Time Per Session. Direction: 1. Channel:2
Mean Time (sec)
Sessions
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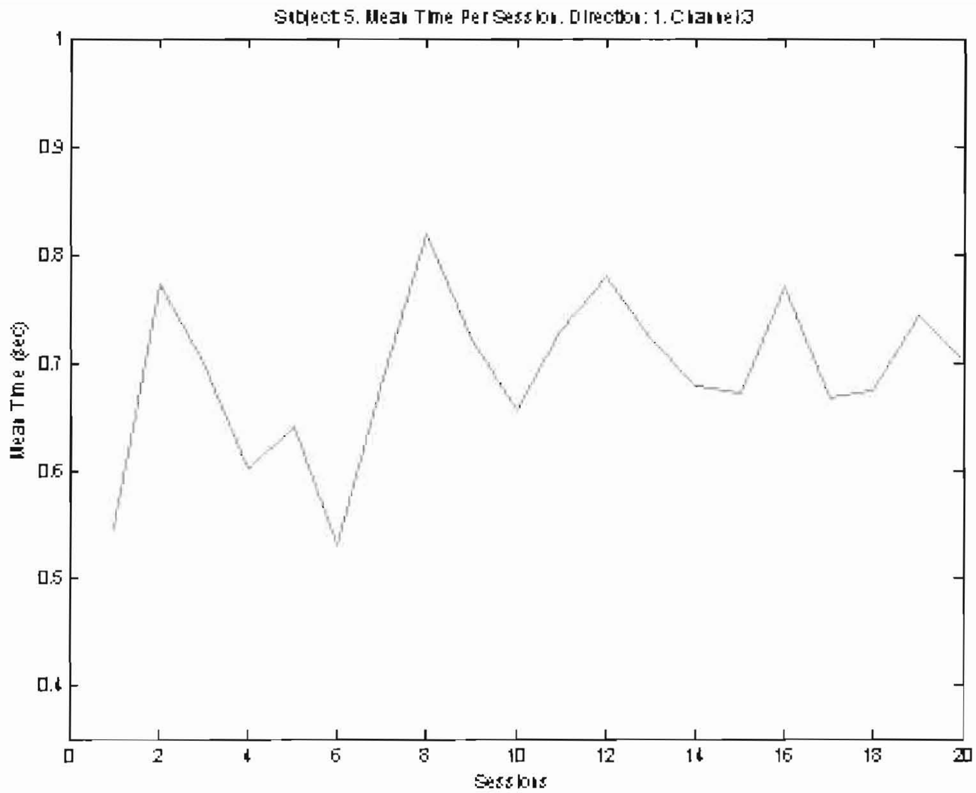
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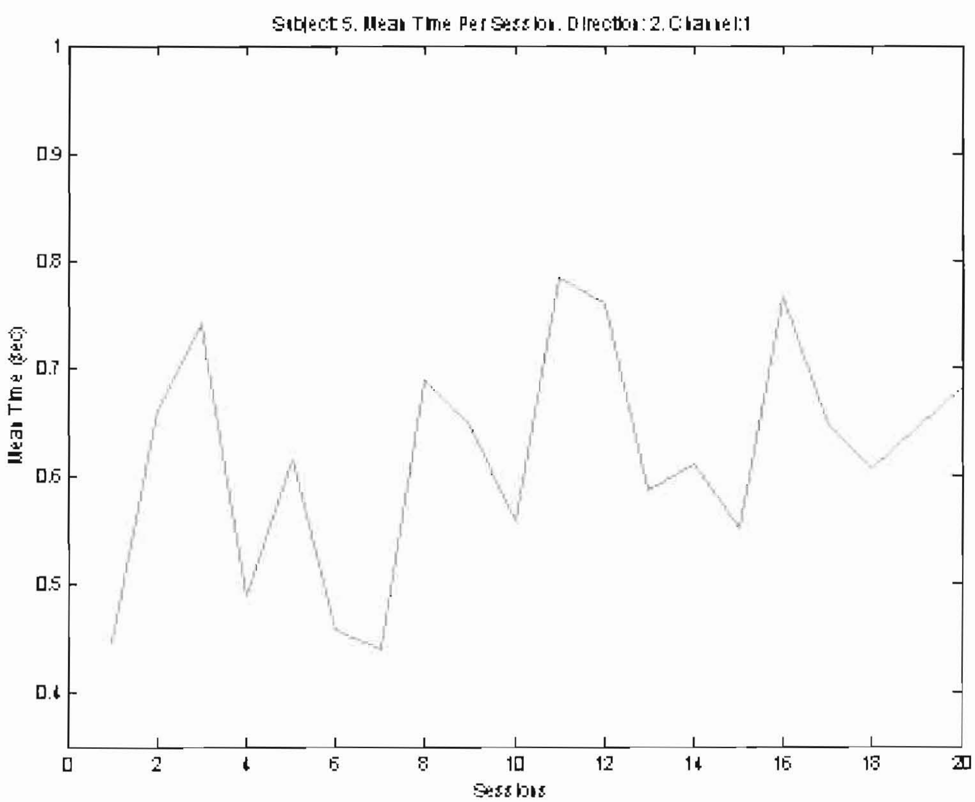
Mean Time (sec)
Sessions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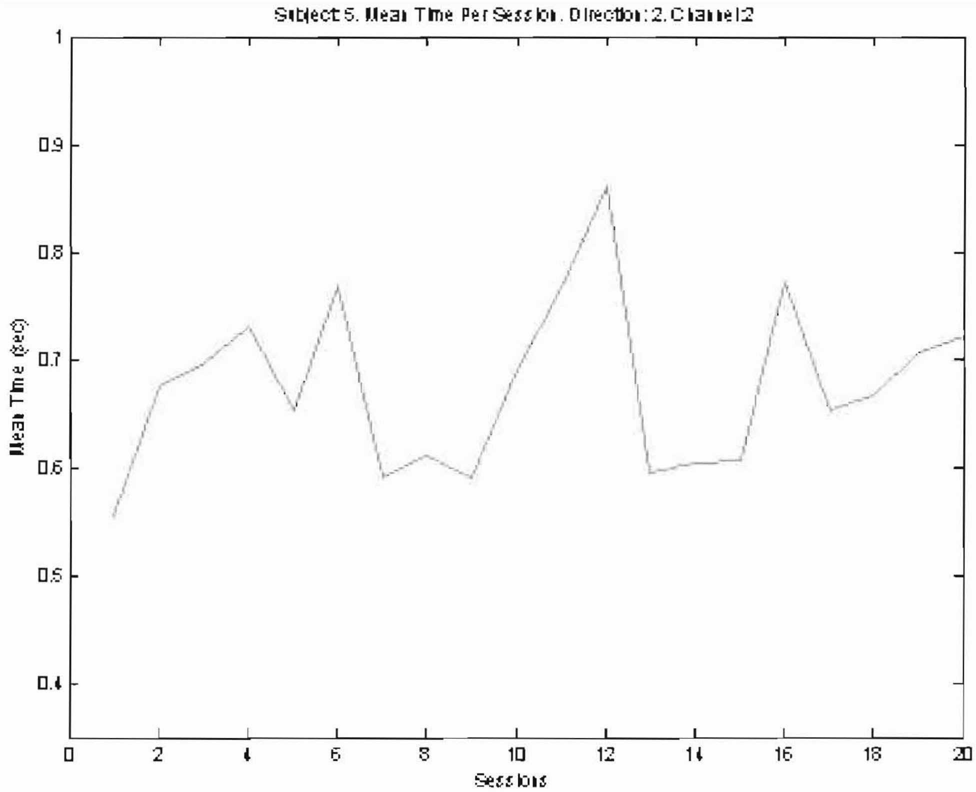
Mean Time (sec)
Sessions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Mean Time (sec)
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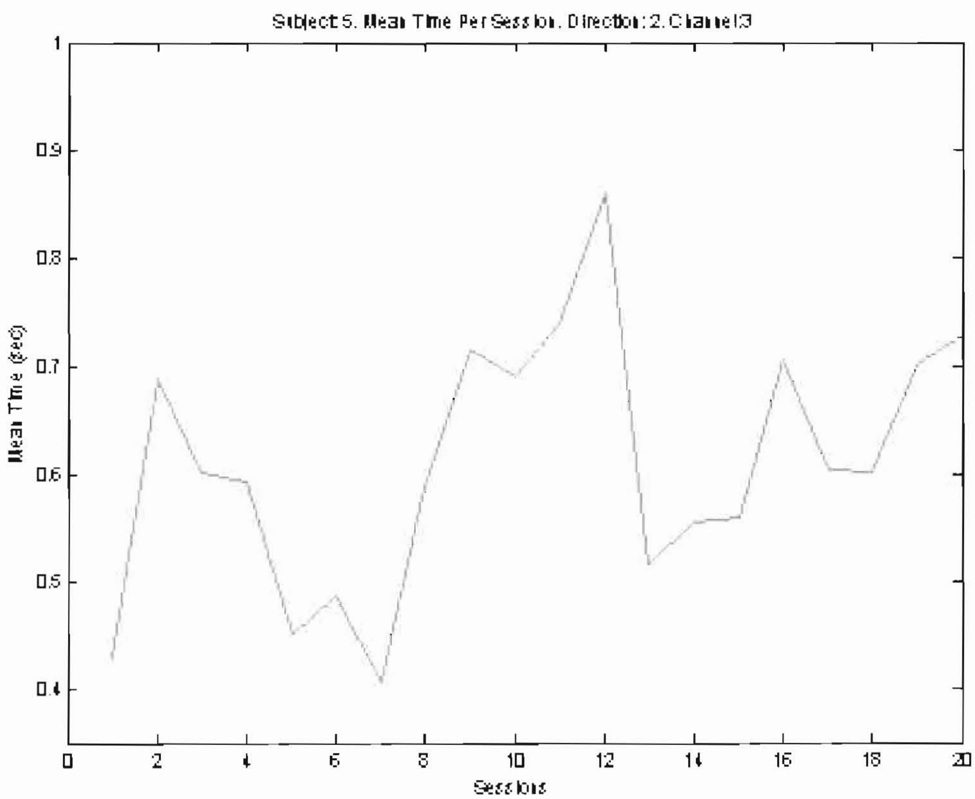
Subject 5. Mean Time Per Session. Direction: 2. Channel 3
Mean Time (sec)
Sessions
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0.9
0.8
0.7
0.6
0.5
0.4
0
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6
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10
12
14
16
18
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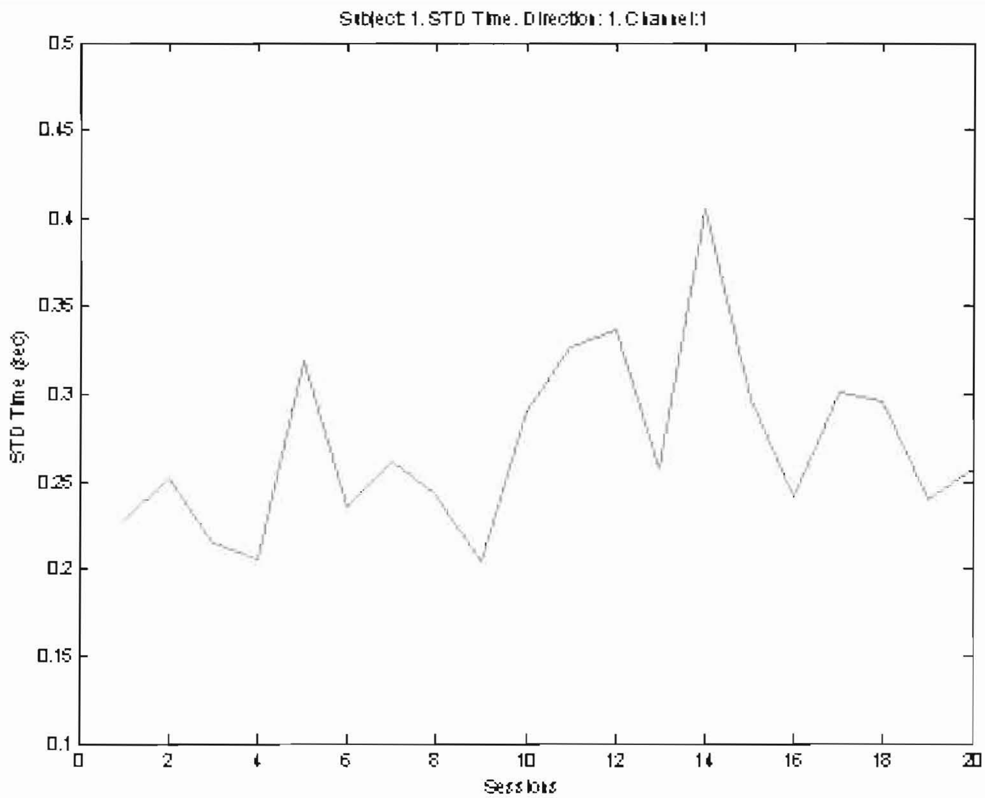
APPENDIX 4: MEAN STANDARD DEVIATION OF REACTION TIME PER SESSION RESULTS


Subject 1. STD Time. Direction: 1. Channel:1
STD Time (sec)
Sessions
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0.4
0.35
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0.2
0.15
0.1
0
2
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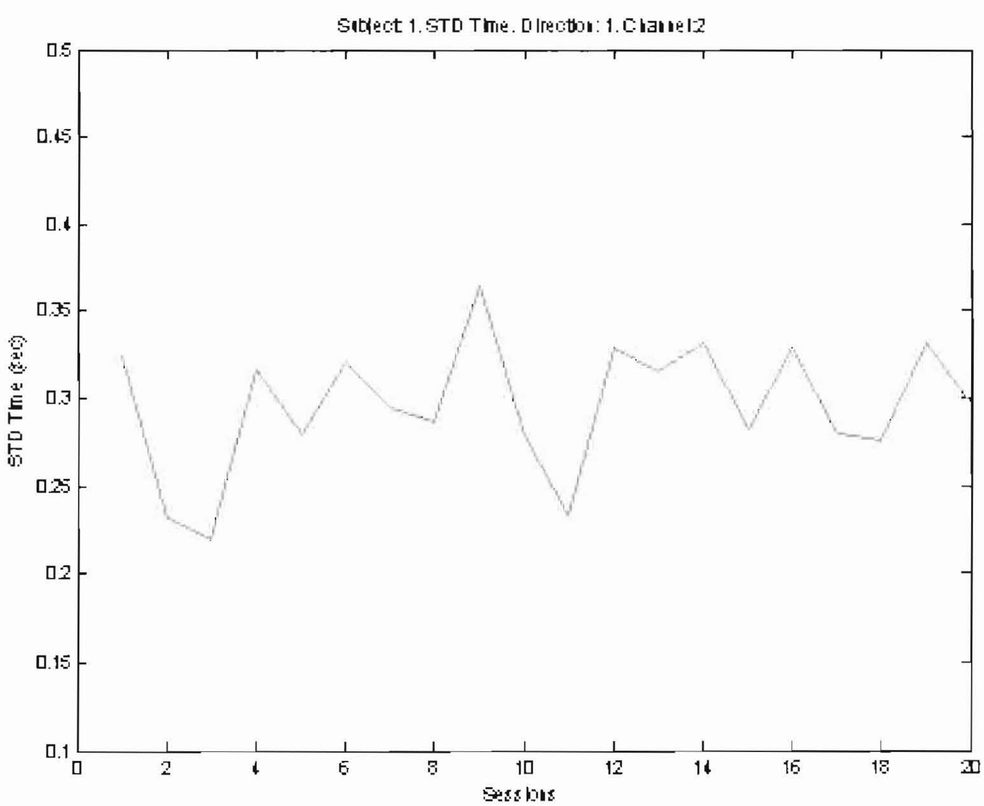
6
8
10
12
14
16
18
20


Subject 1. STD Time. Direction: 1. Channel:2
STD Time (sec)
Sessions
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0.4
0.35
0.3
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0.2
0.15
0.1
0
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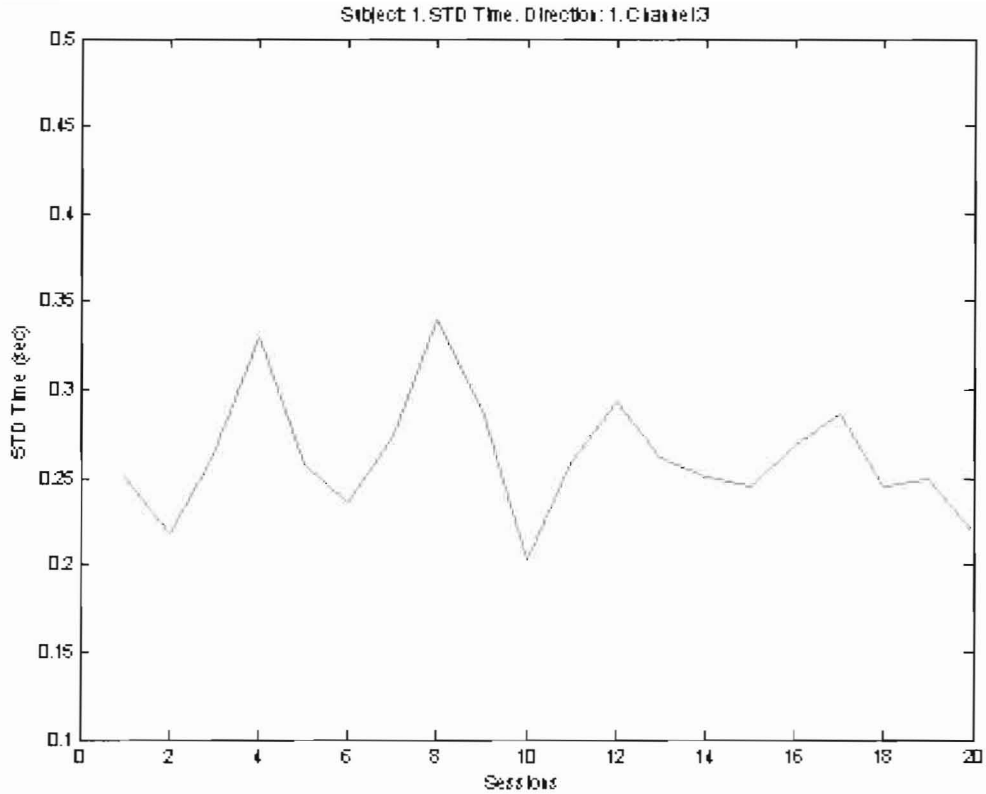
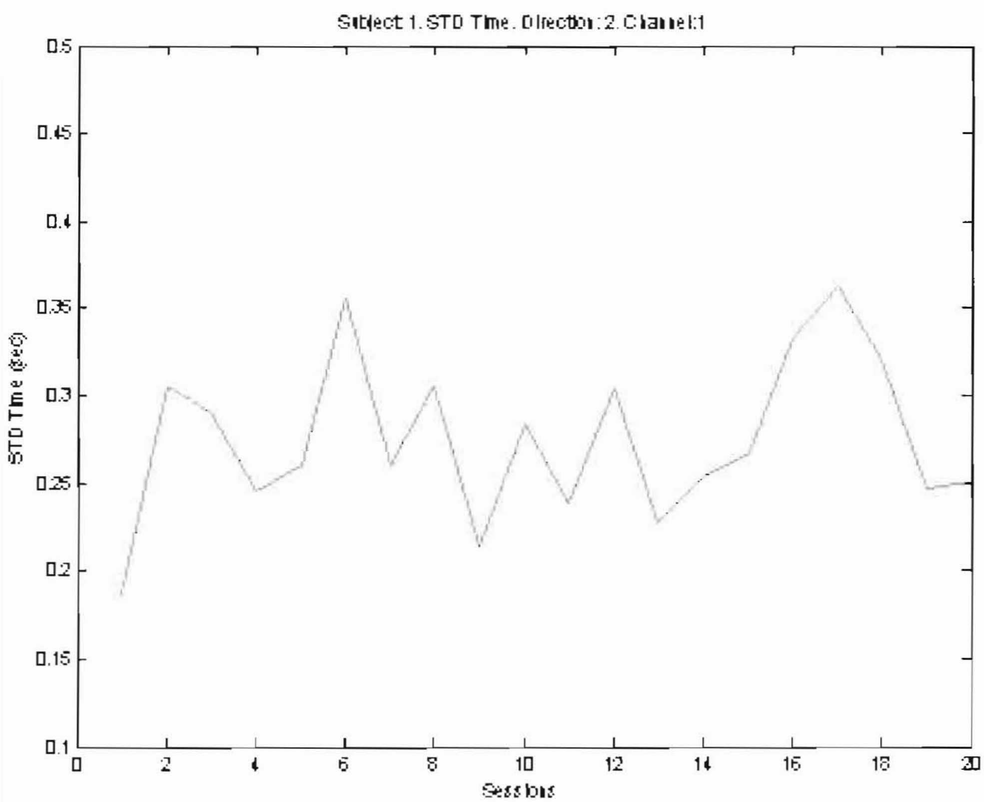
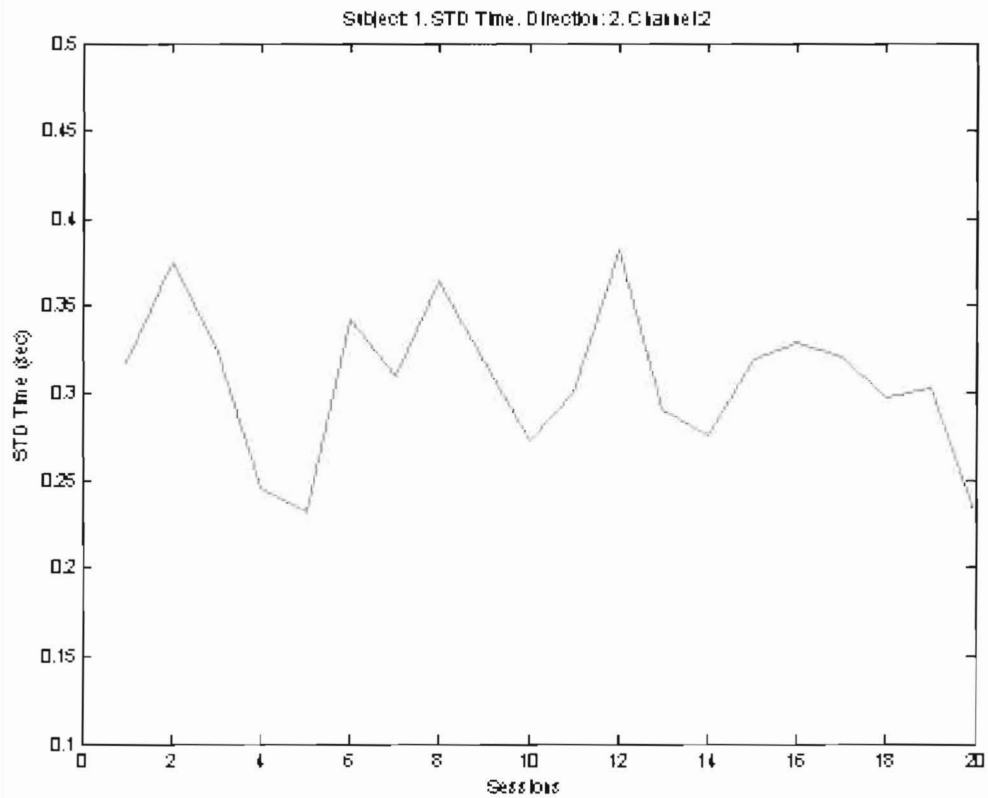
4
6
8
10
12
14
16
18
20


Subject 1. STD Time. Direction: 1. Channel:3
STD Time (sec)
Sessions


Subject 1. STD Time. Direction: 2. Channel:1
STD Time (sec)
Sessions


Subject 1. STD Time. Direction: 2. Channel:2
STD Time (sec)
Sessions
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0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
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6
8
10
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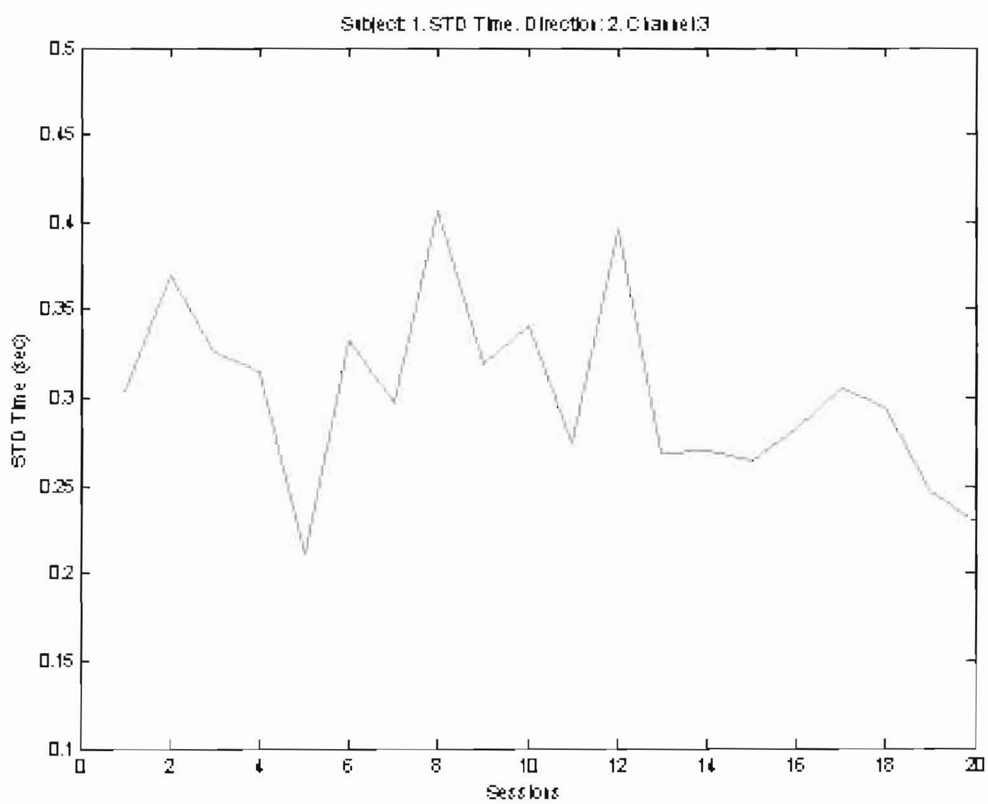
Subject 1. STD Time. Direction: 2. Channel:3
STD Time (sec)
Sessions
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0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
2
4
6
8
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12
14
16
18
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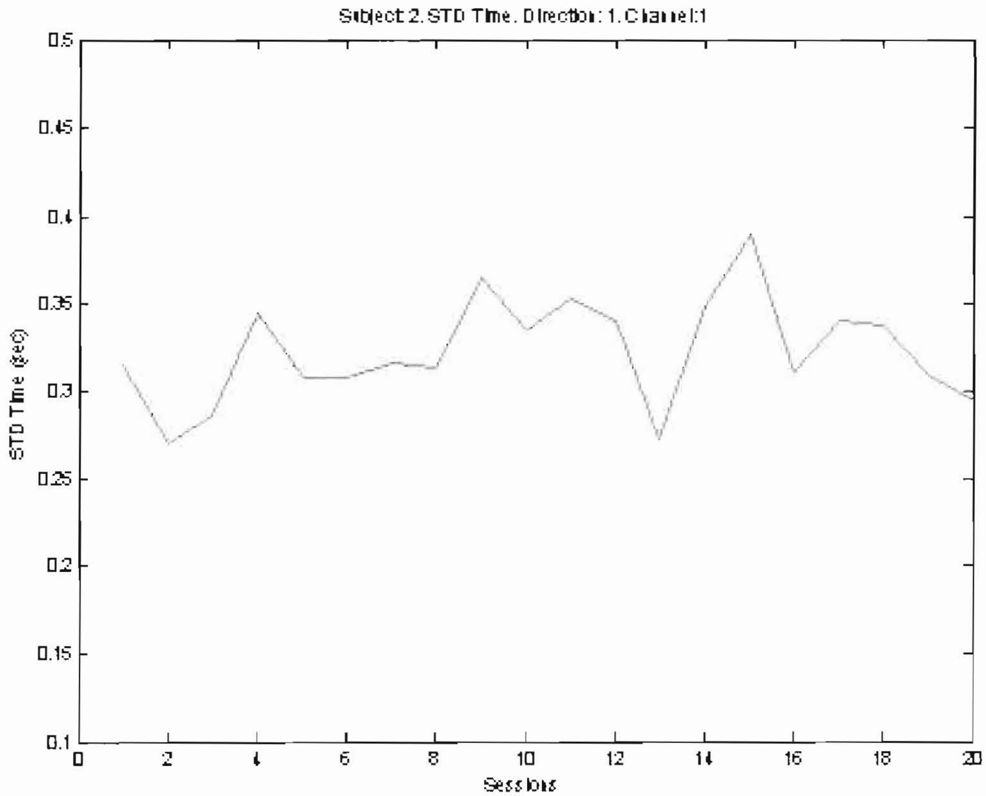

Subject 2. STD Time. Direction: 1. Channel:1
STD Time (sec)
Sessions
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0.15
0.2
0.25
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0.4
0.45
0.5
0
2
4
6
8
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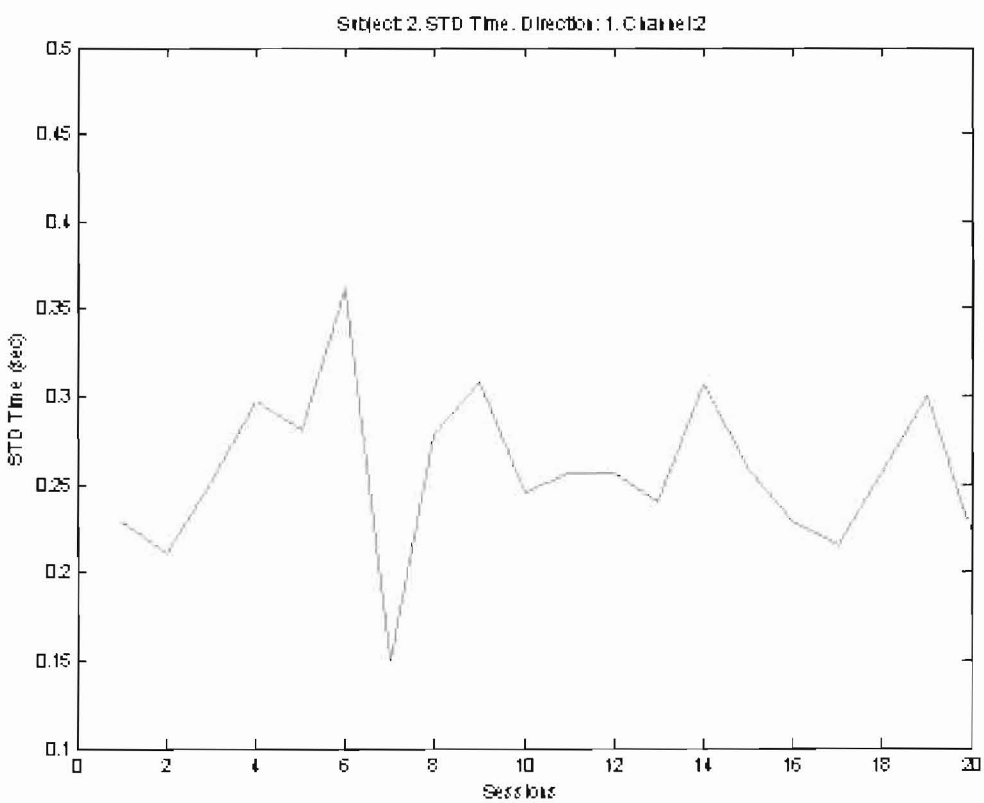
12
14
16
18
20



Subject 2. STD Time. Direction: 1. Channel:2
STD Time (sec)
Sessions
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0.2
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0.45
0.5
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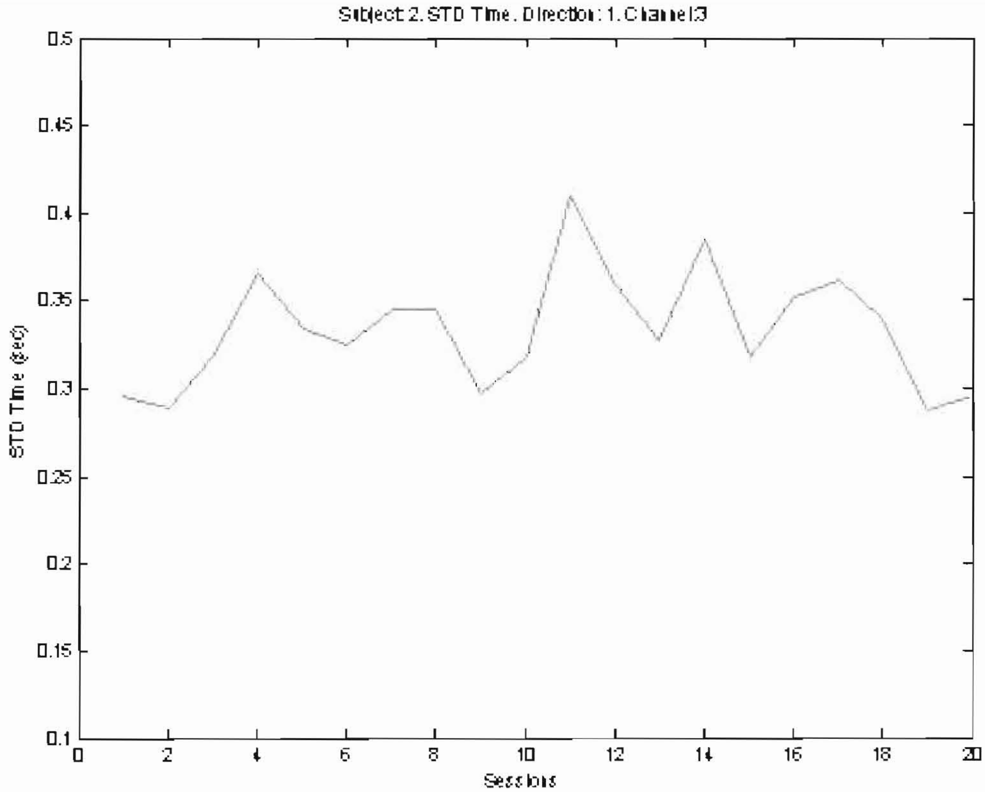
Subject 2. STD Time. Direction: 1. Channel:3
STD Time (sec)
Sessions
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0.4
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0.1
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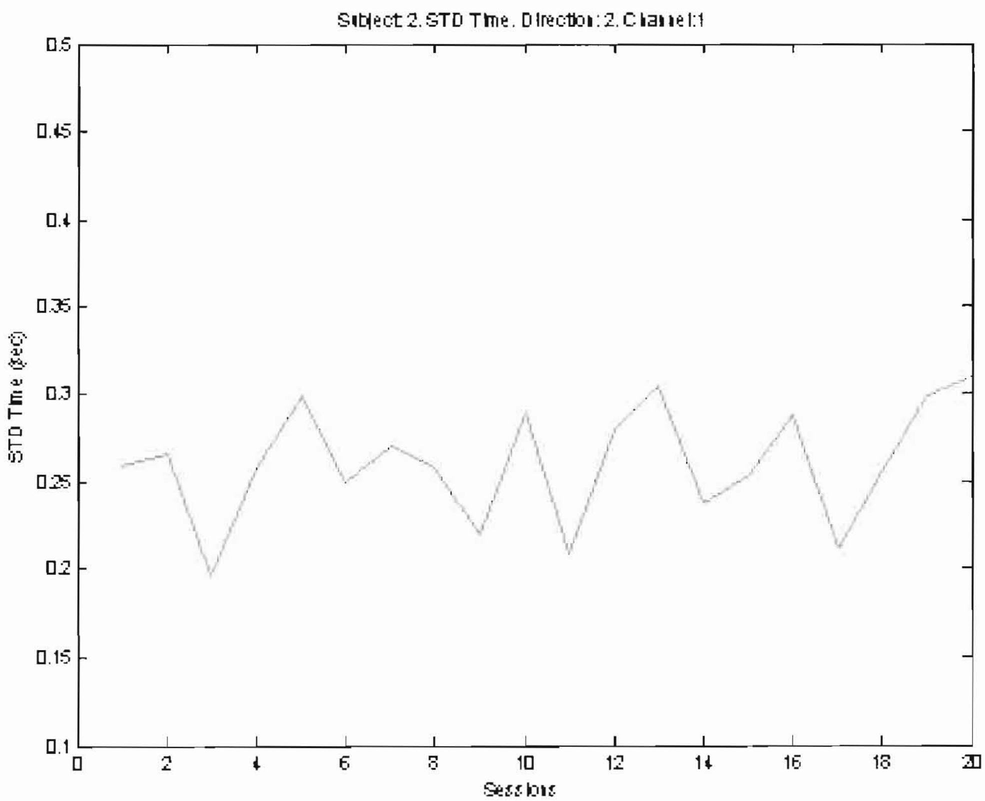
Subject 2. STD Time. Direction: 2. Channel:1
STD Time (sec)
Sessions
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0.4
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0.2
0.15
0.1
0
2
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6
8
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18
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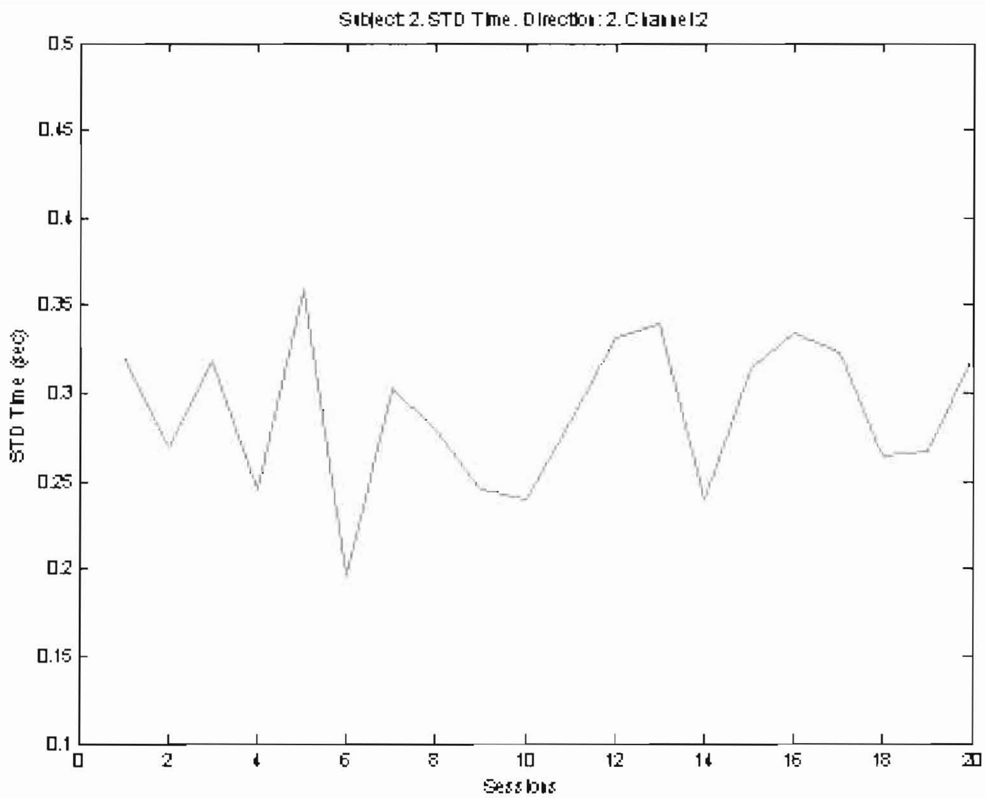
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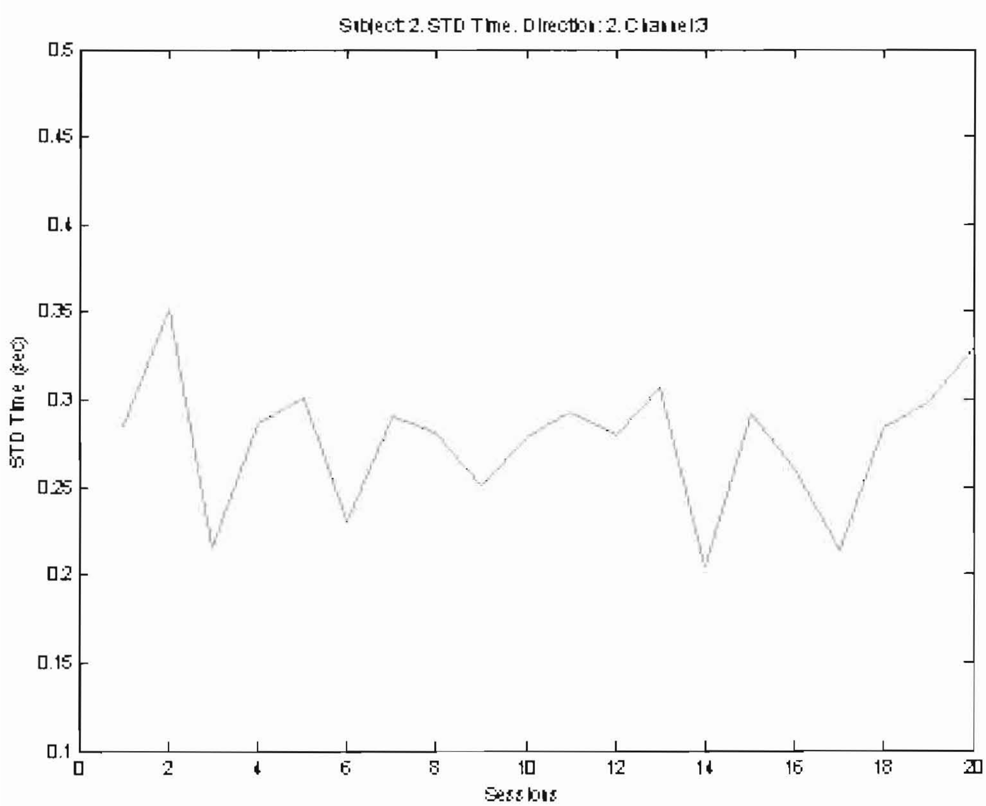
STD Time (sec)
Sessions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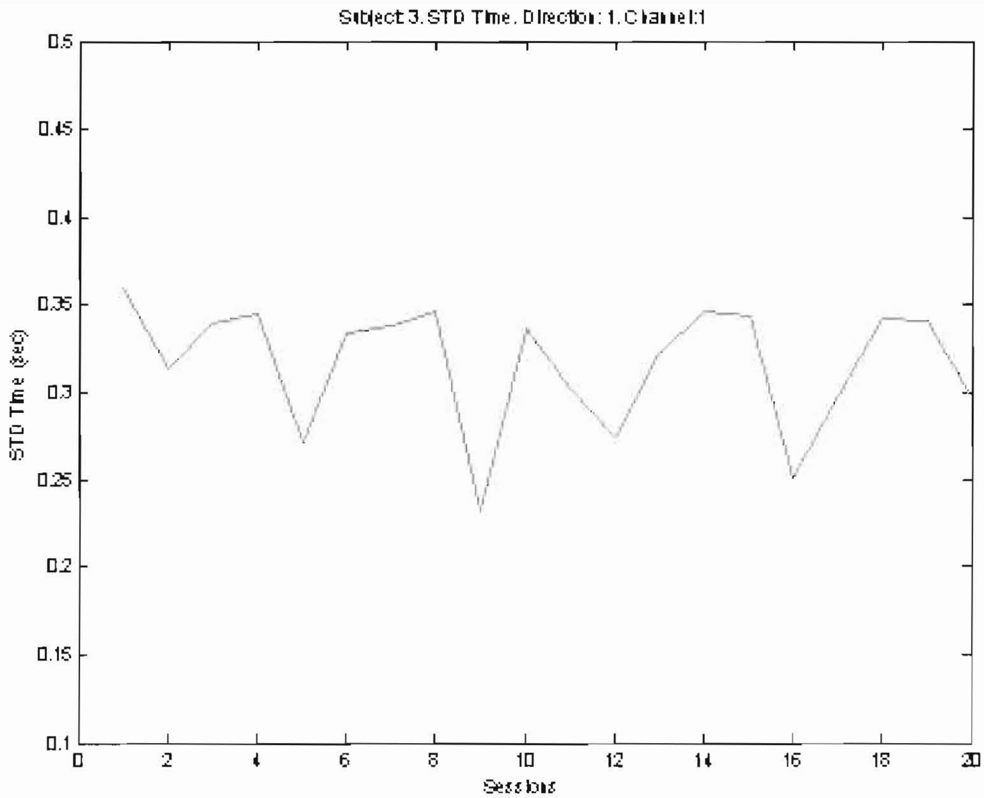
STD Time (sec)
Sessions


Subject 3. STD Time. Direction: 1. Channel:1
STD Time (sec)
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0.2
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0.1
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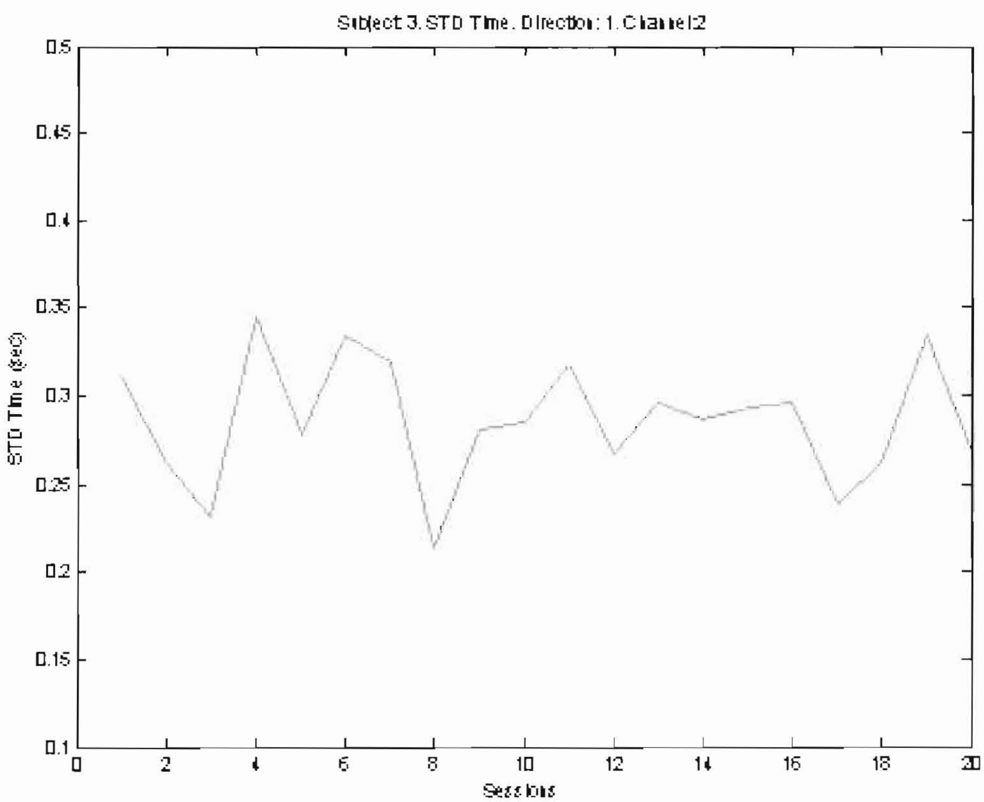
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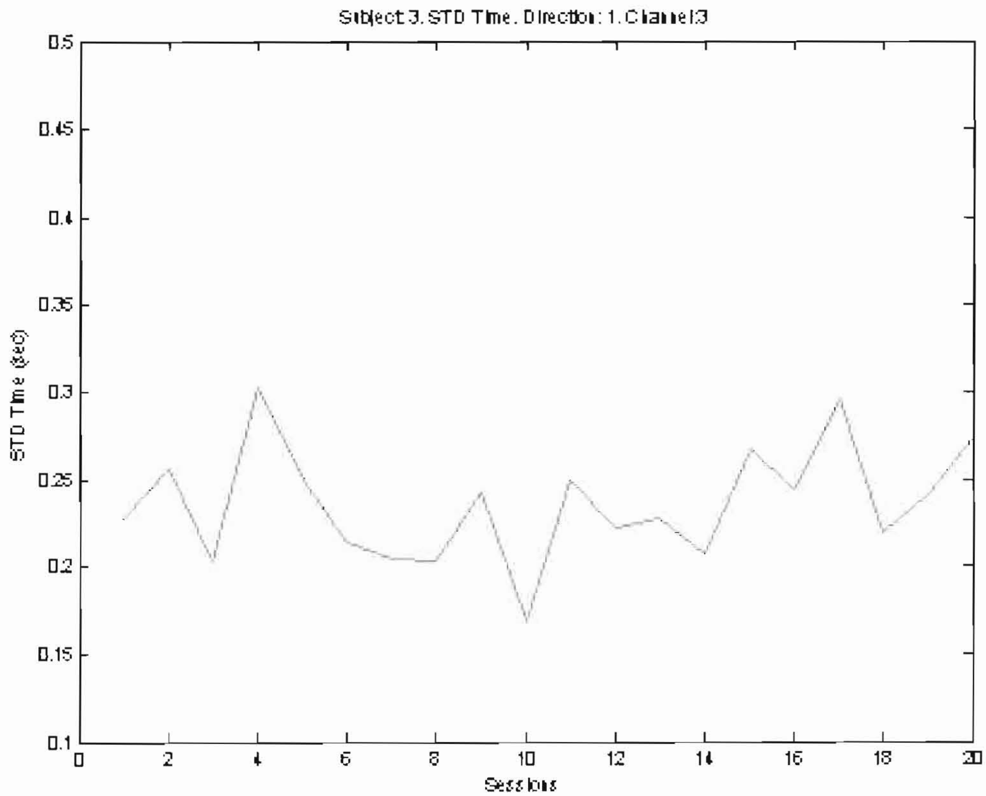
Subject 3. STD Time. Direction: 1. Channel:3
STD Time (sec)
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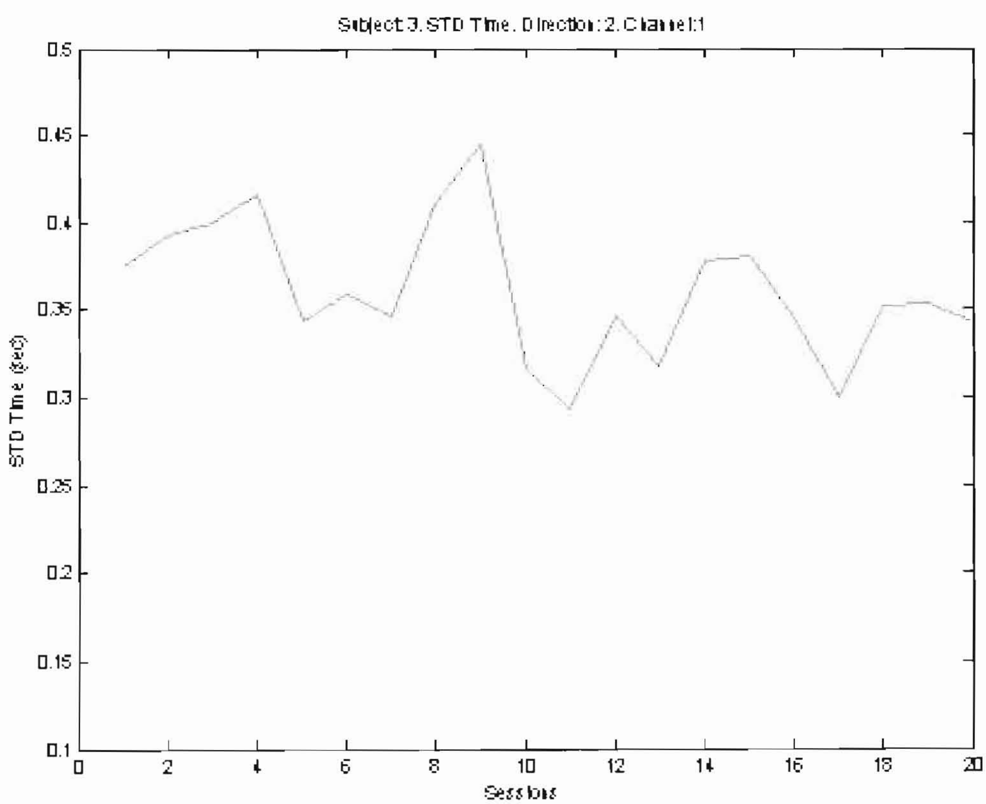
Subject 3. STD Time. Direction: 2. Channel:1
STD Time (sec)
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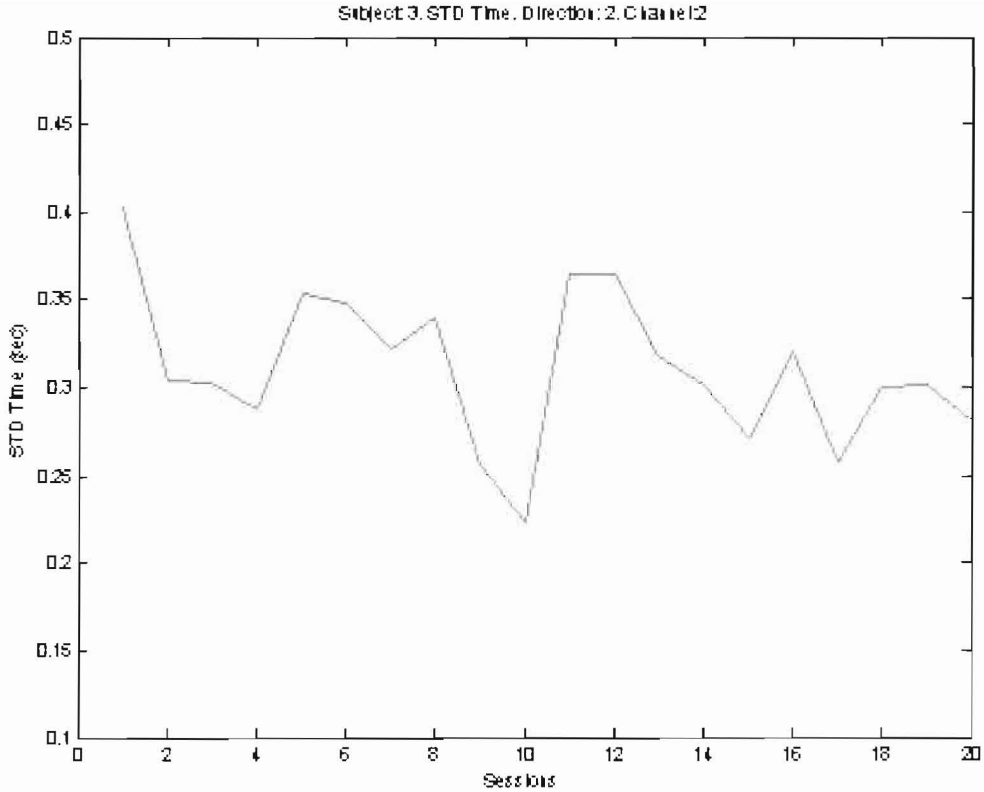
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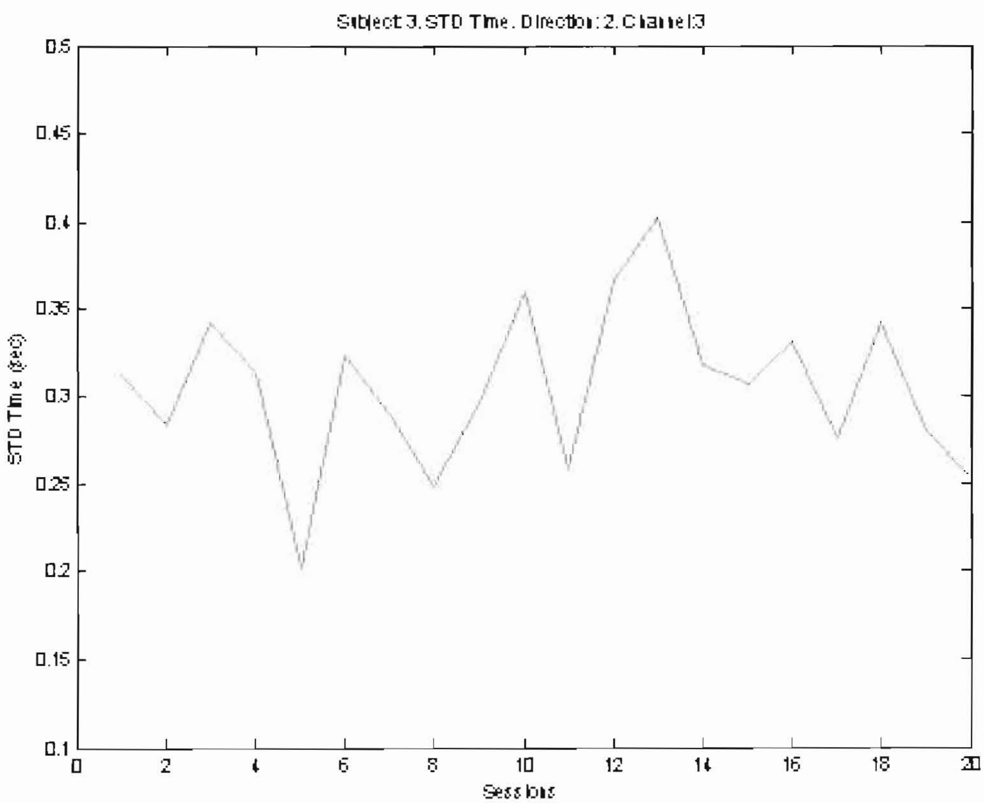
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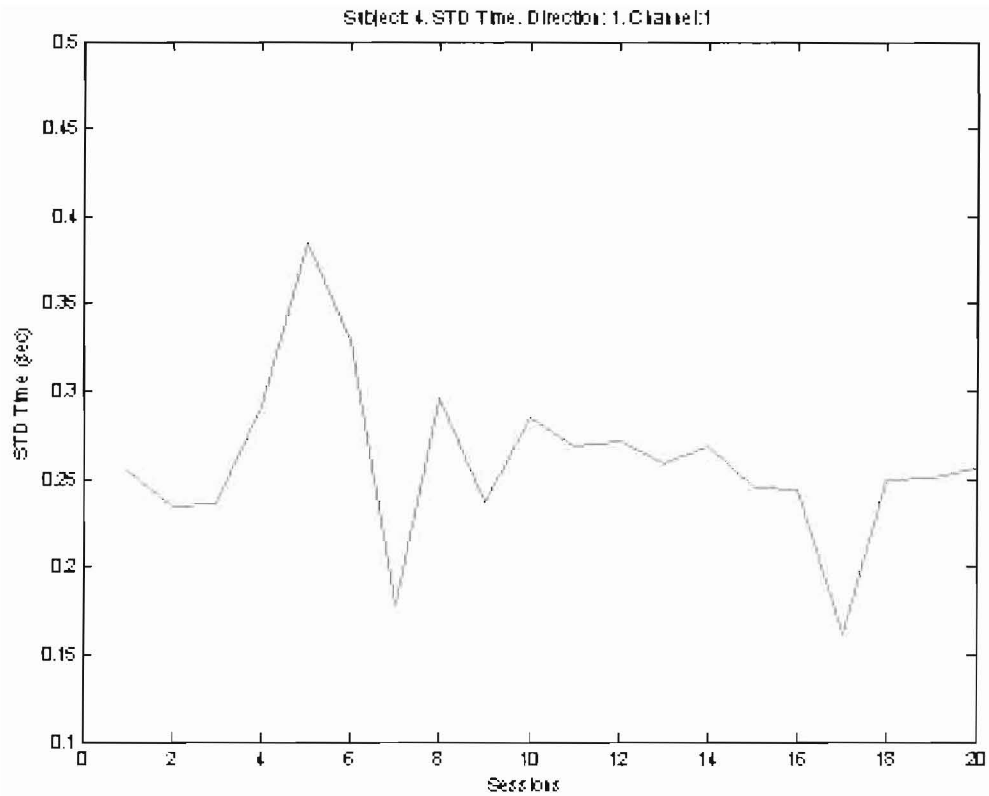
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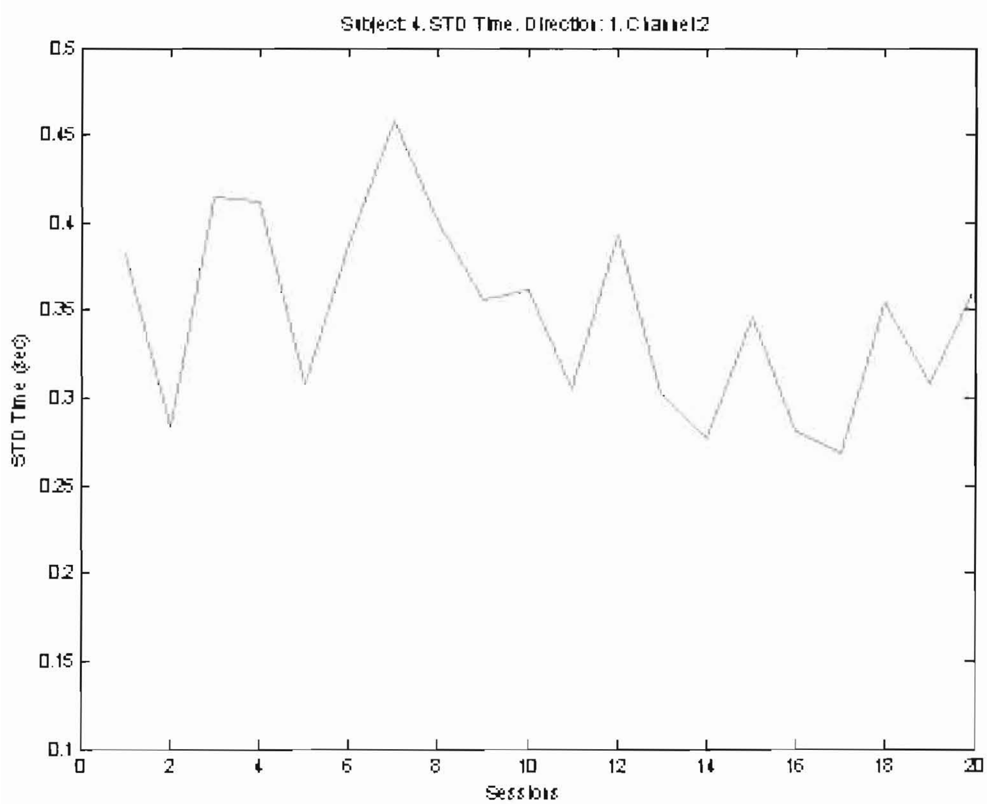
STD Time (sec)
Sessions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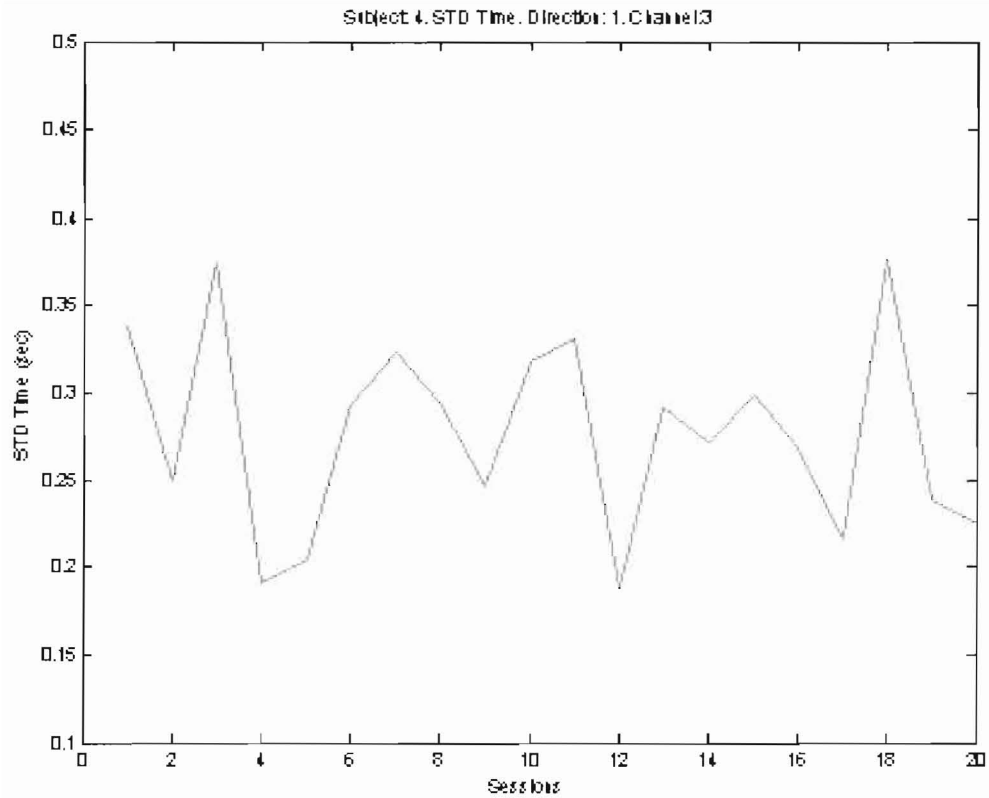
STD Time (sec)
Sessions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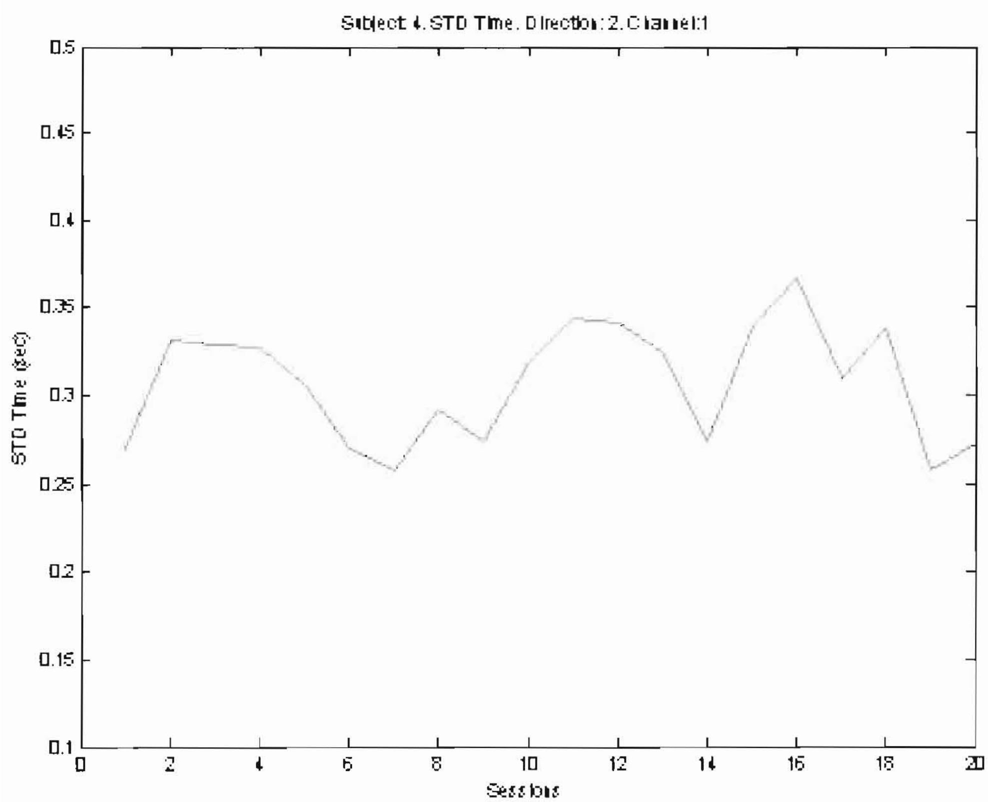
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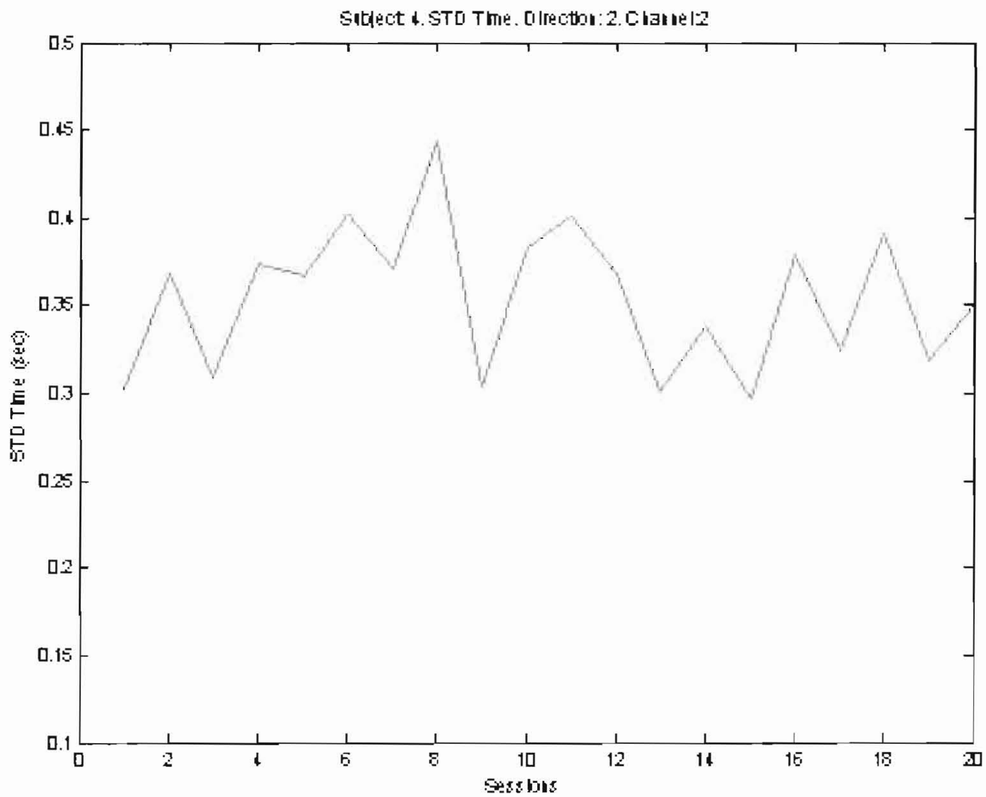
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STD Time (sec)
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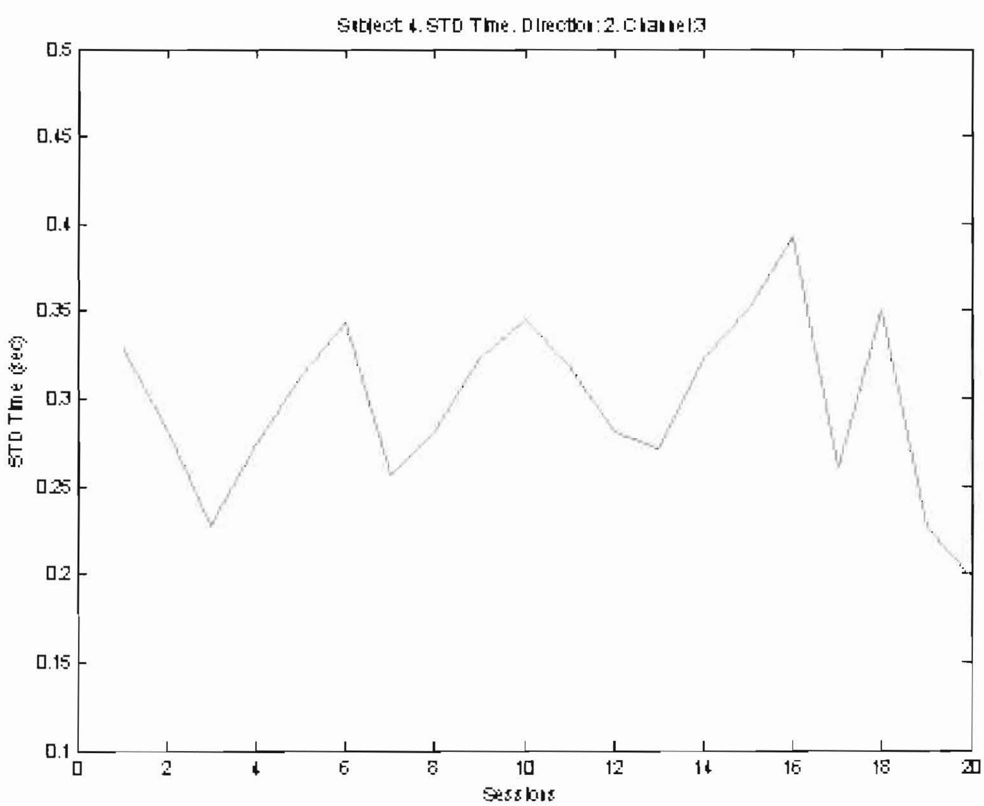
Subject 4. STD Time. Direction: 2. Channel:3
STD Time (sec)
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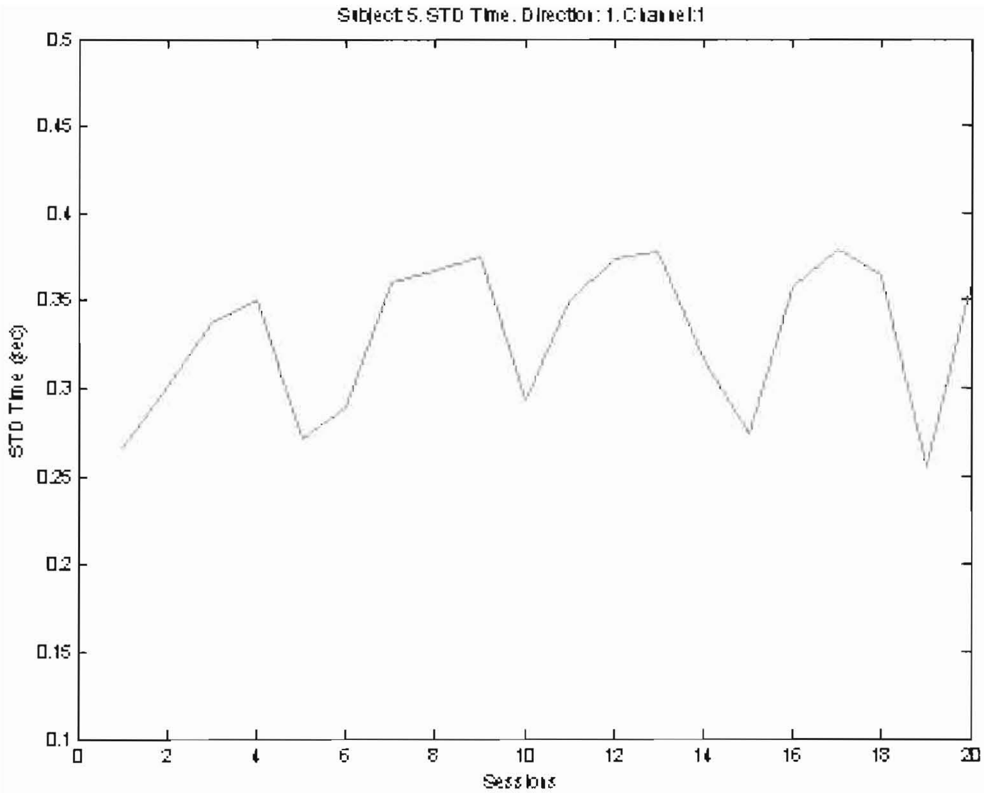
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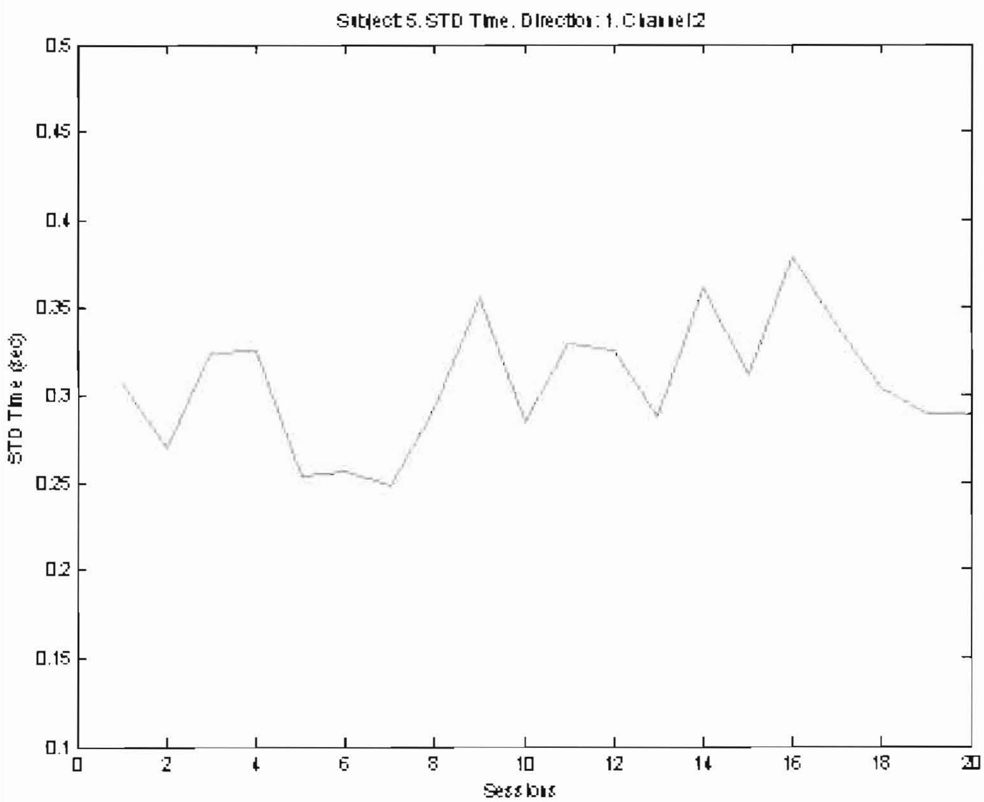
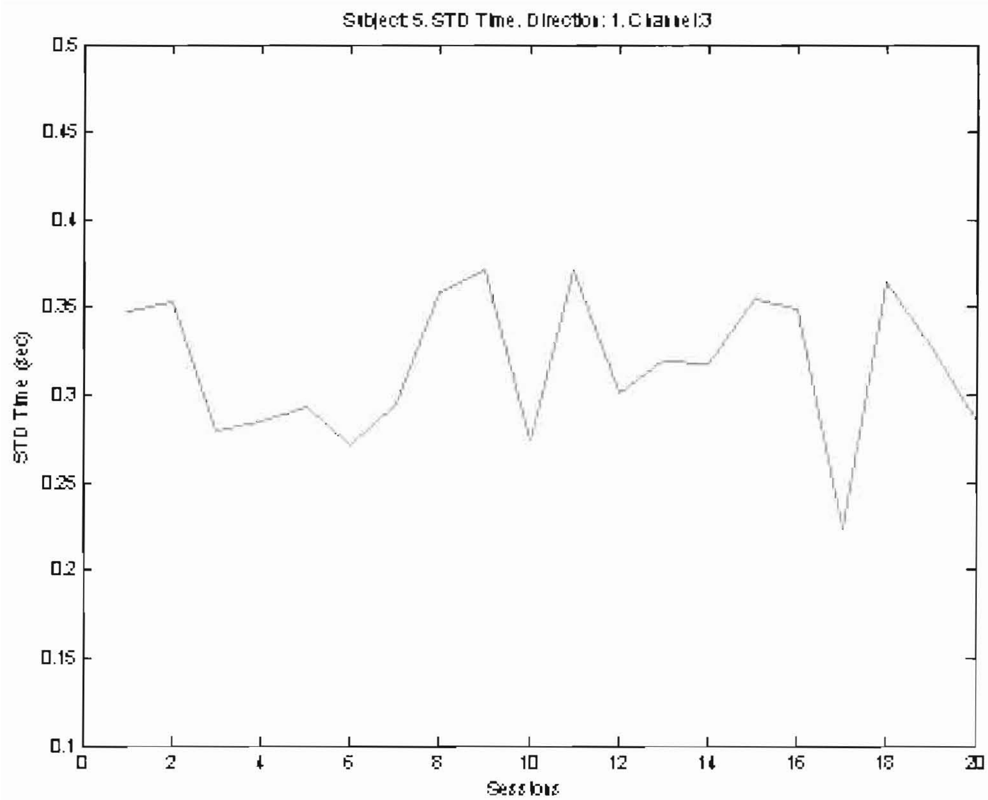
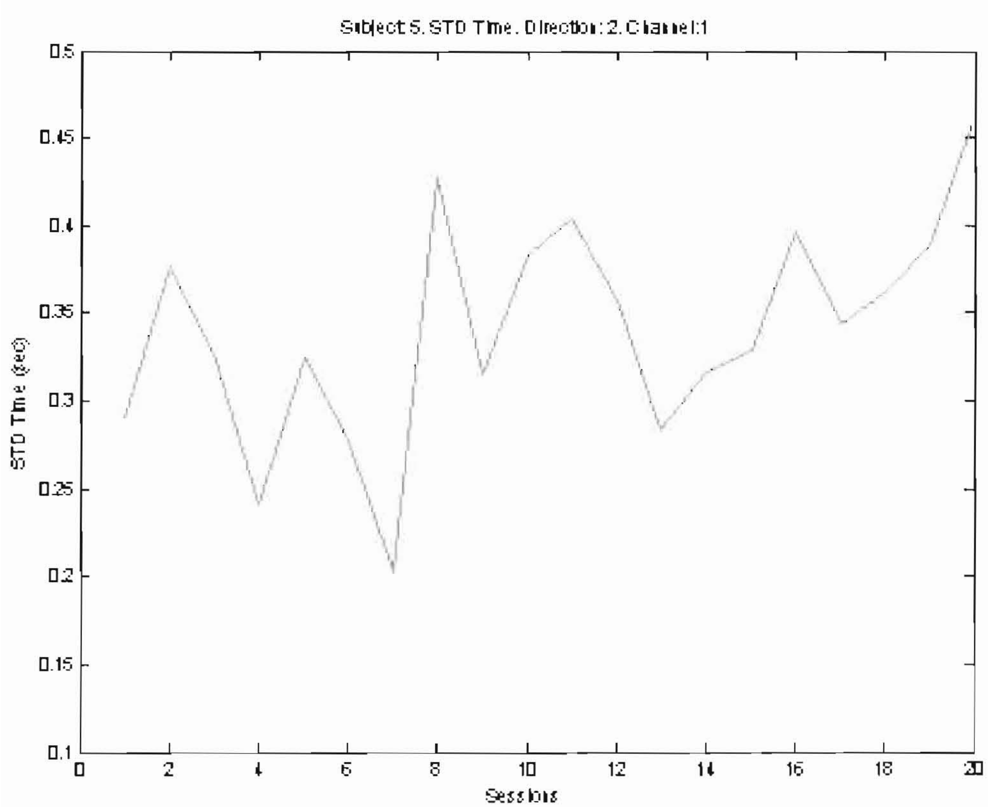
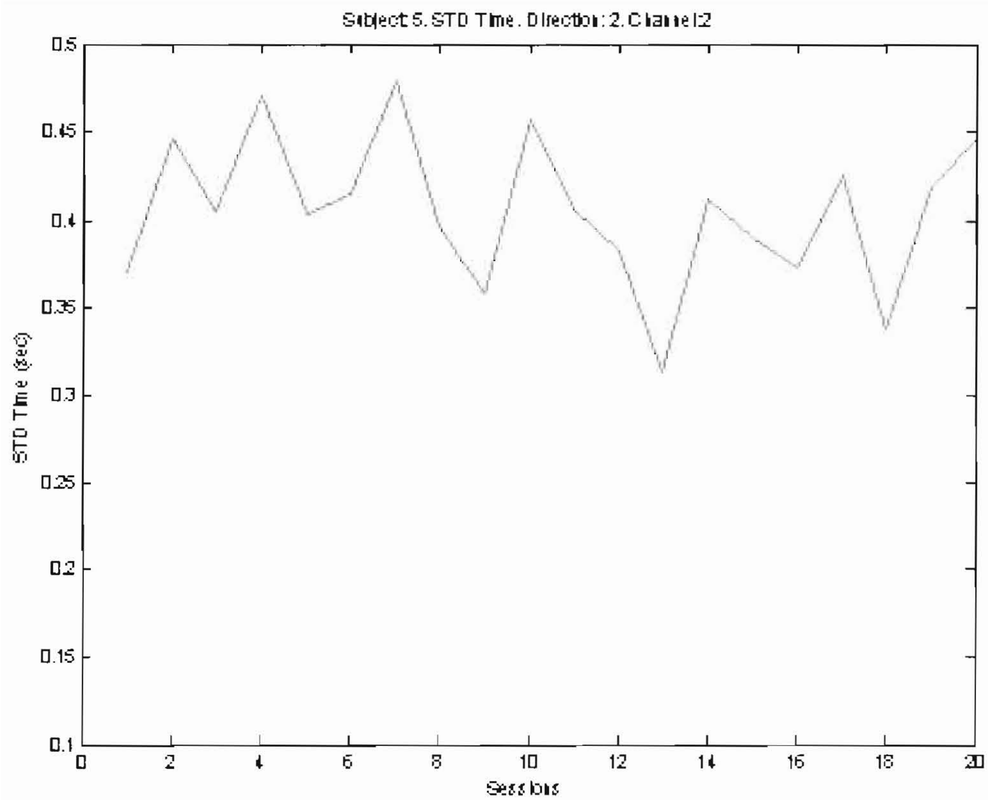
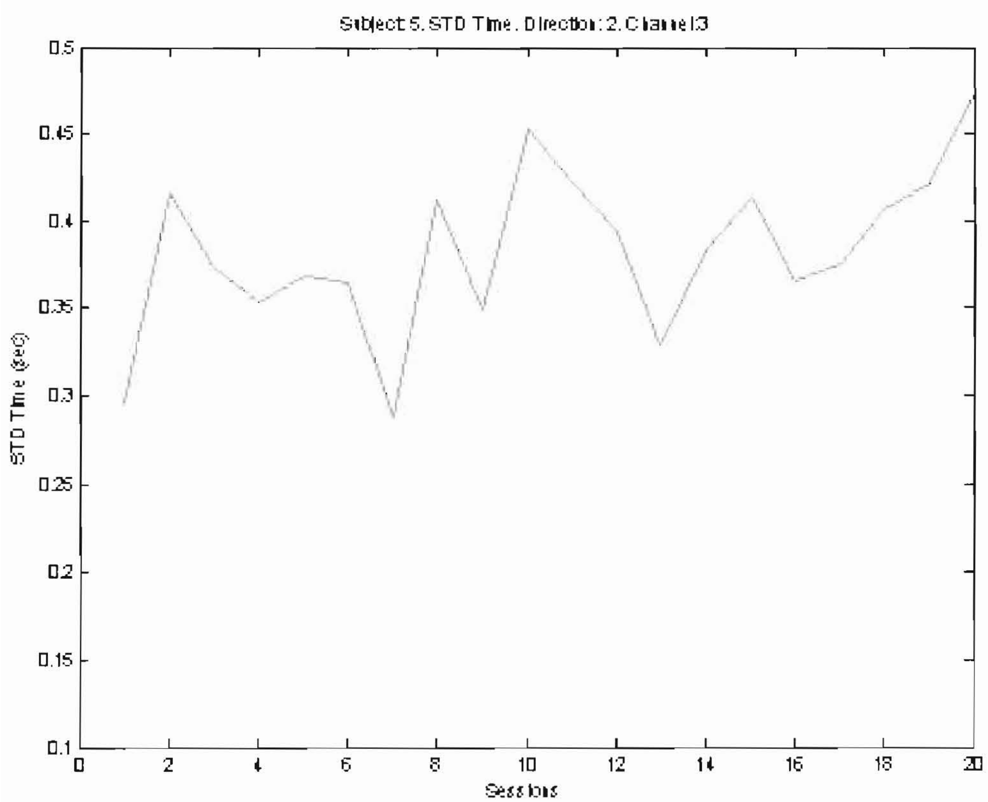
STD Time (sec)
Sessions


Subject 5. STD Time. Direction: 1. Channel:2
STD Time (sec)
Sessions

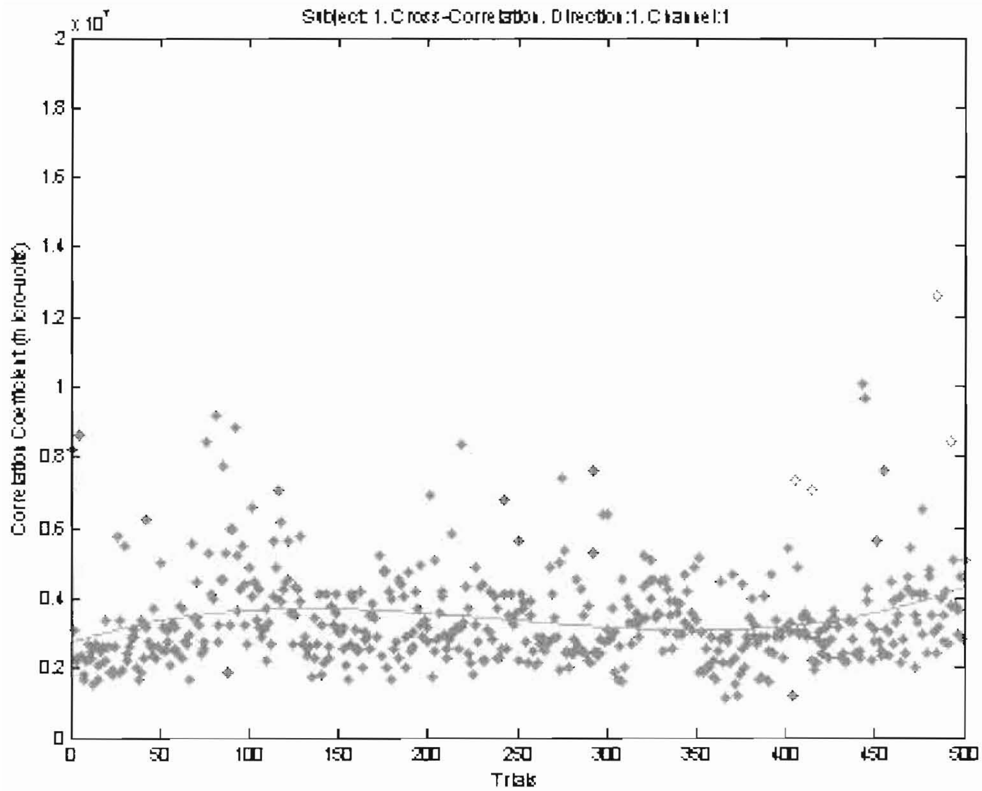

Subject 5. STD Time. Direction: 1. Channel:3
STD Time (sec)
Sessions
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
2
4
6
8
10
12
14
16
18
20

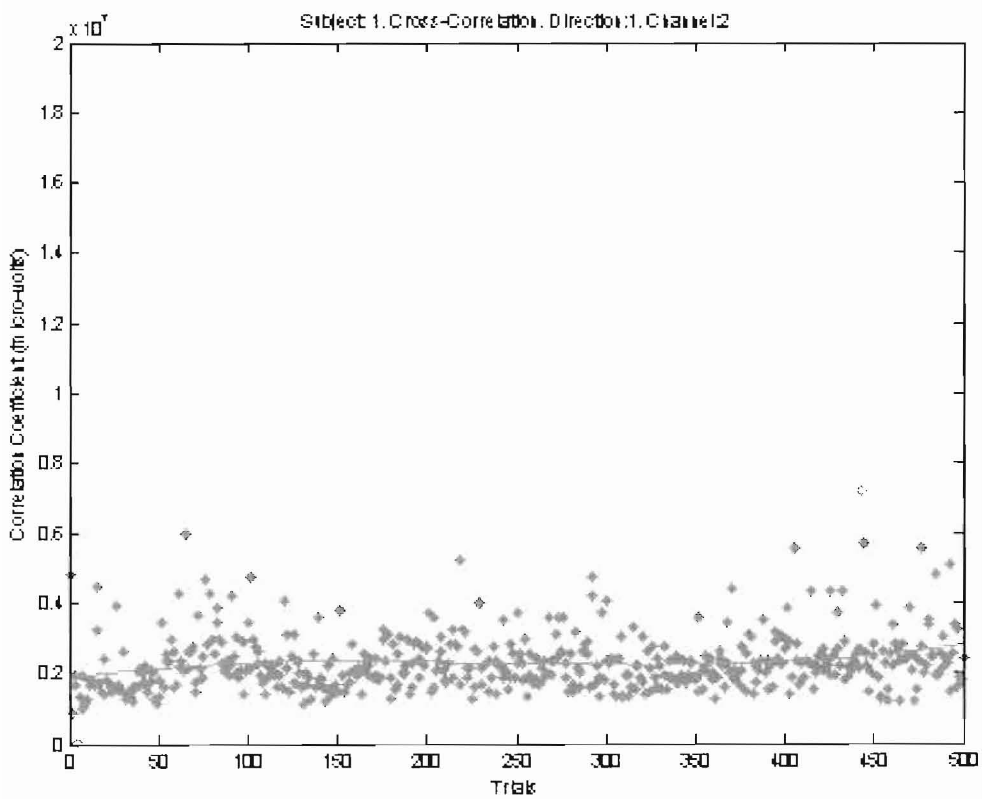

Subject 5. STD Time. Direction: 2. Channel:1
STD Time (sec)
Sessions
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
2
4
6
8
10
12
14
16
18
20

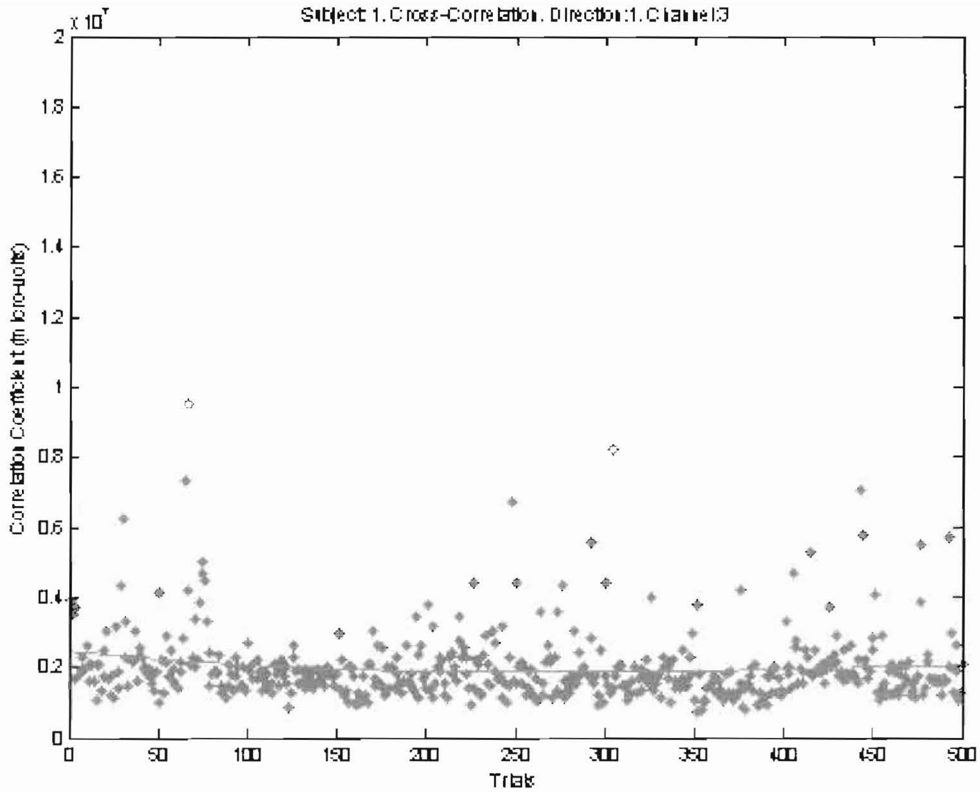

Subject 5. STD Time. Direction: 2. Channel 2
STD Time (sec)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
2
4
6
8
10
12
14
16
18
20
Sessions

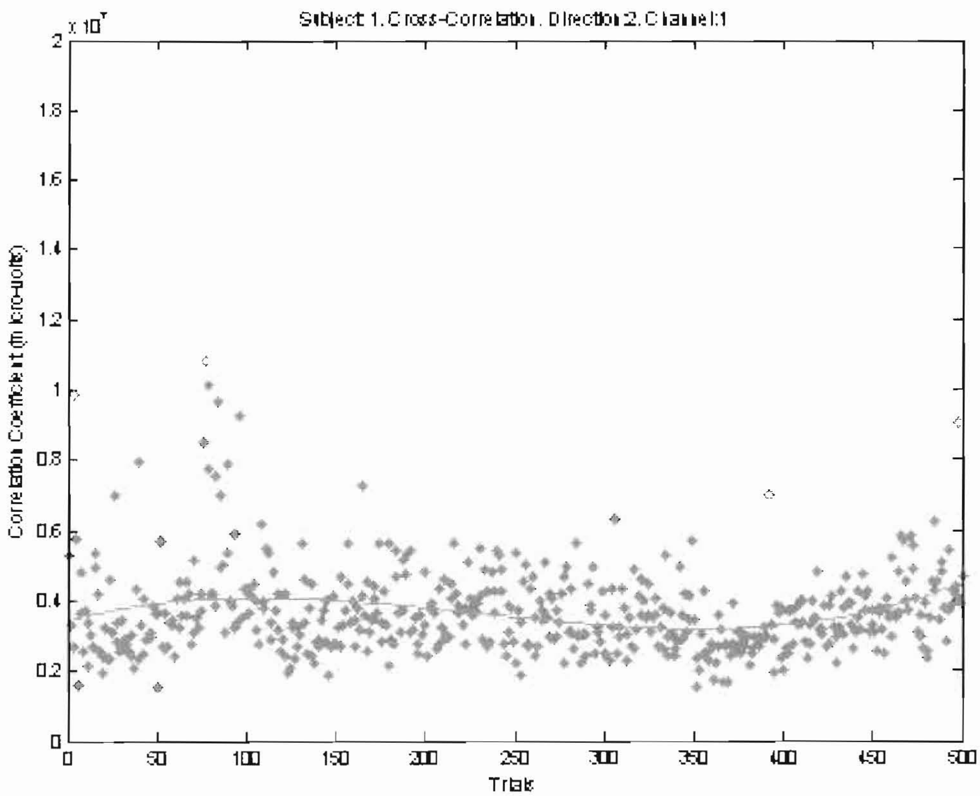

Subject 5. STD Time. Direction: 2. Channel 3
STD Time (sec)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
2
4
6
8
10
12
14
16
18
20
Sessions

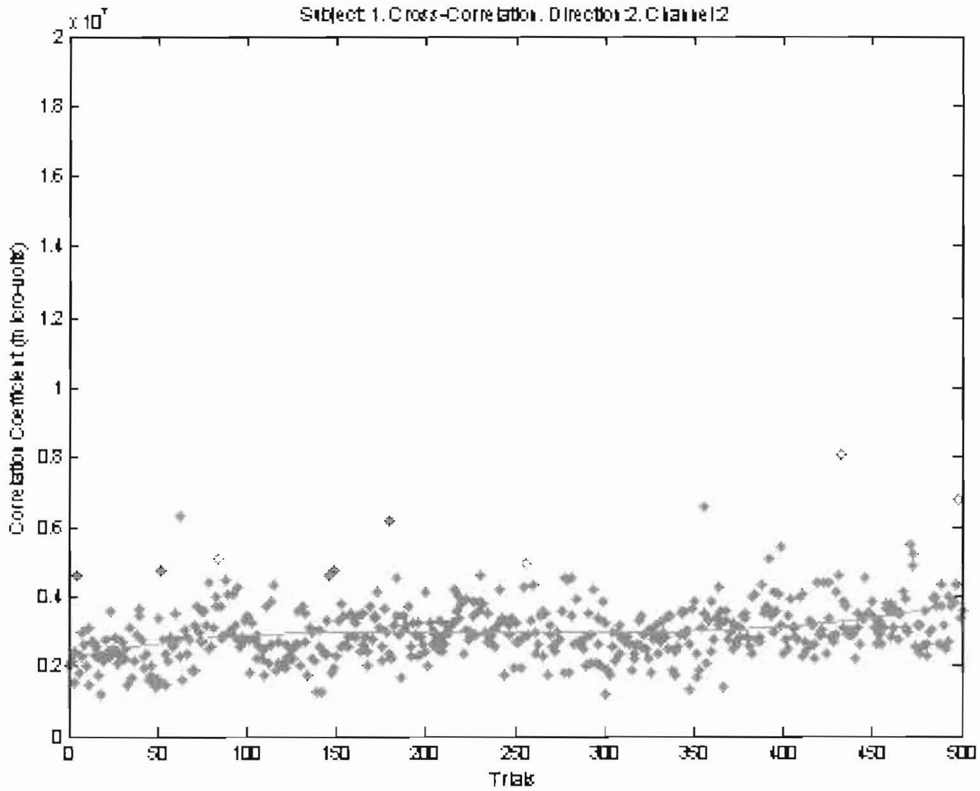
APPENDIX 5: CORRELATION COEFFICIENTS RESULTS

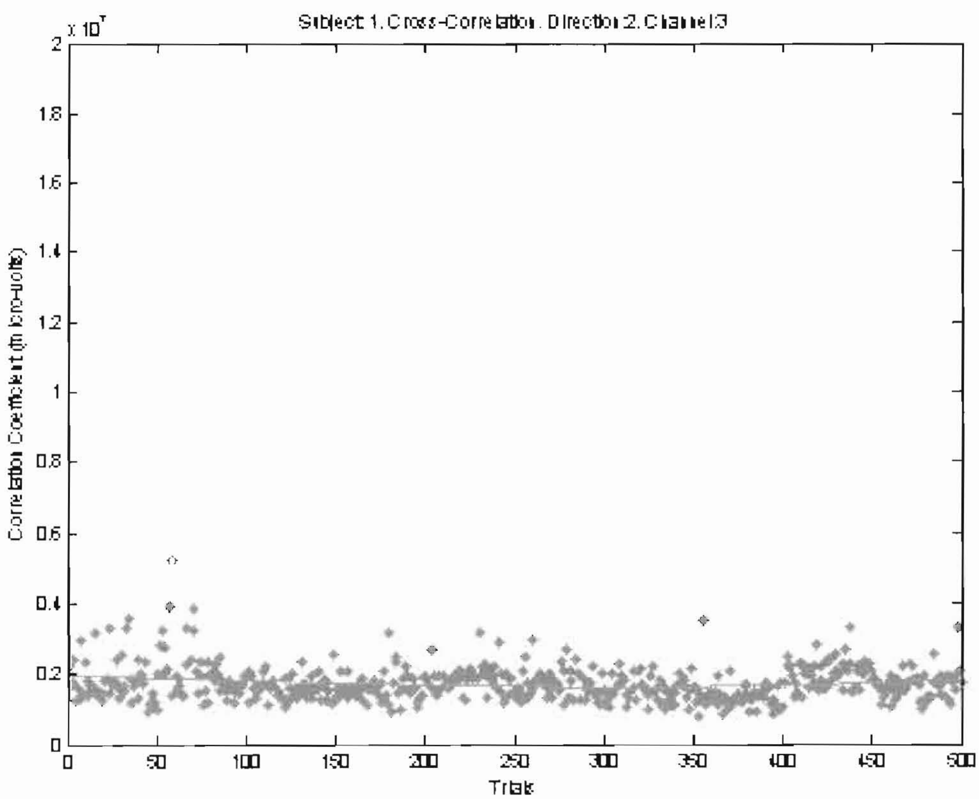

Subject 1. Cross-Correlation. Direction:1. Channel:1
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
100
150
200
250
300
350
400
450
500

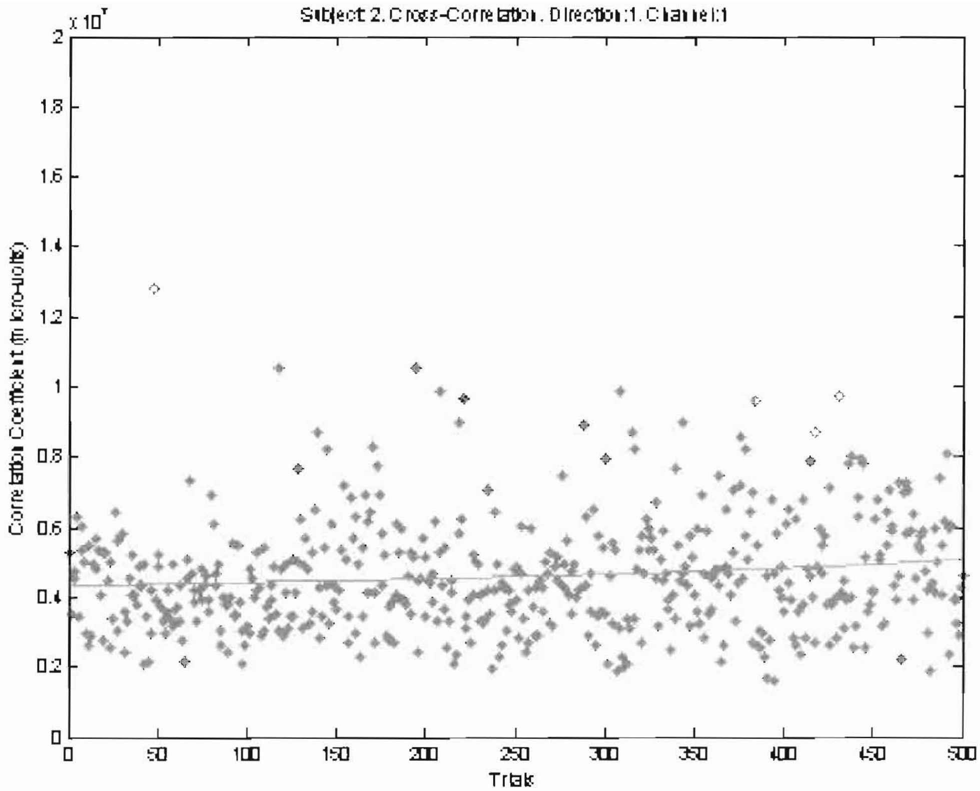

Subject 1. Cross-Correlation. Direction:1. Channel:2
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
100
150
200
250
300
350
400
450
500

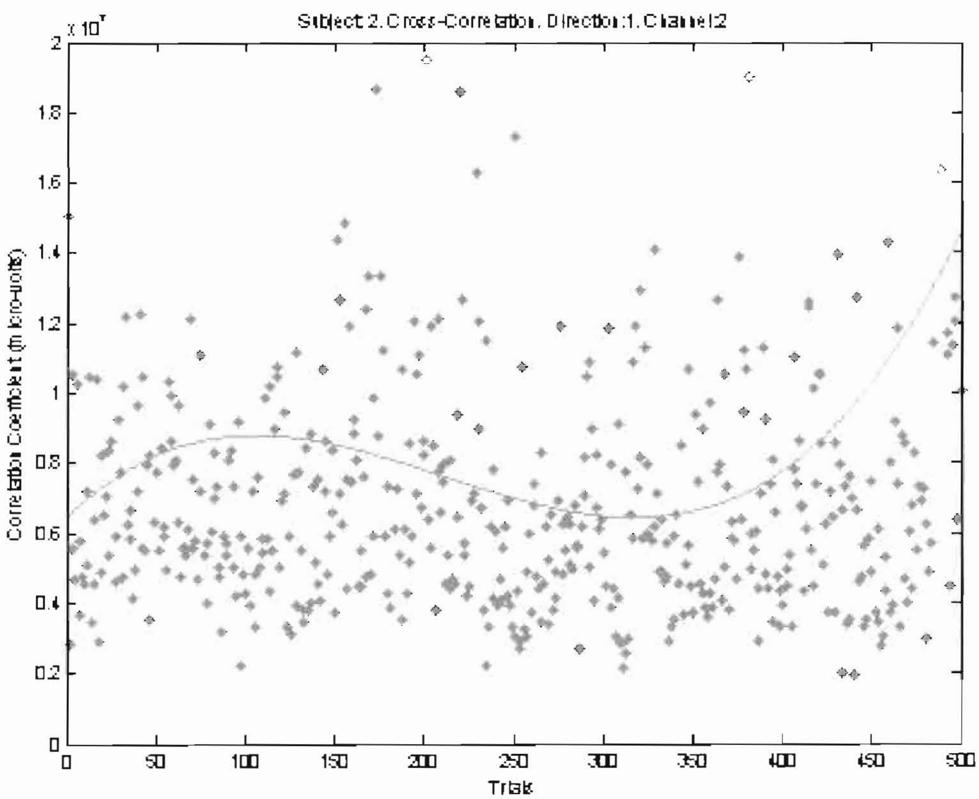

Subject 1. Cross-Correlation. Direction:1. Channel:3
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

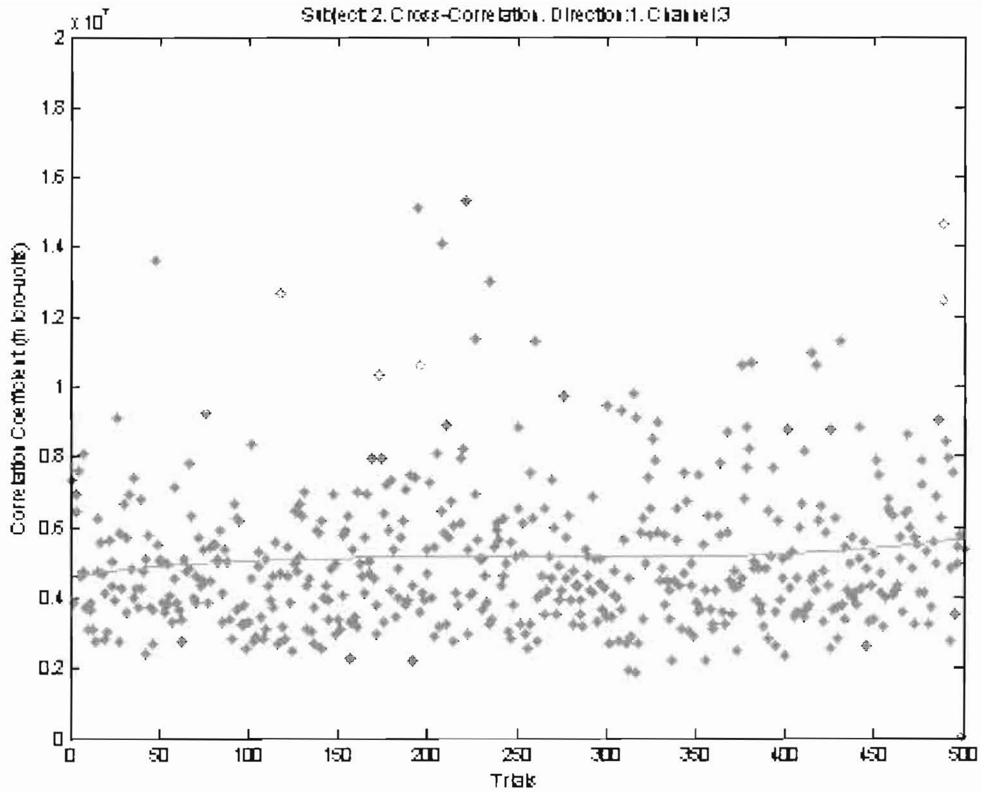

Subject 1. Cross-Correlation. Direction:2. Channel:1
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

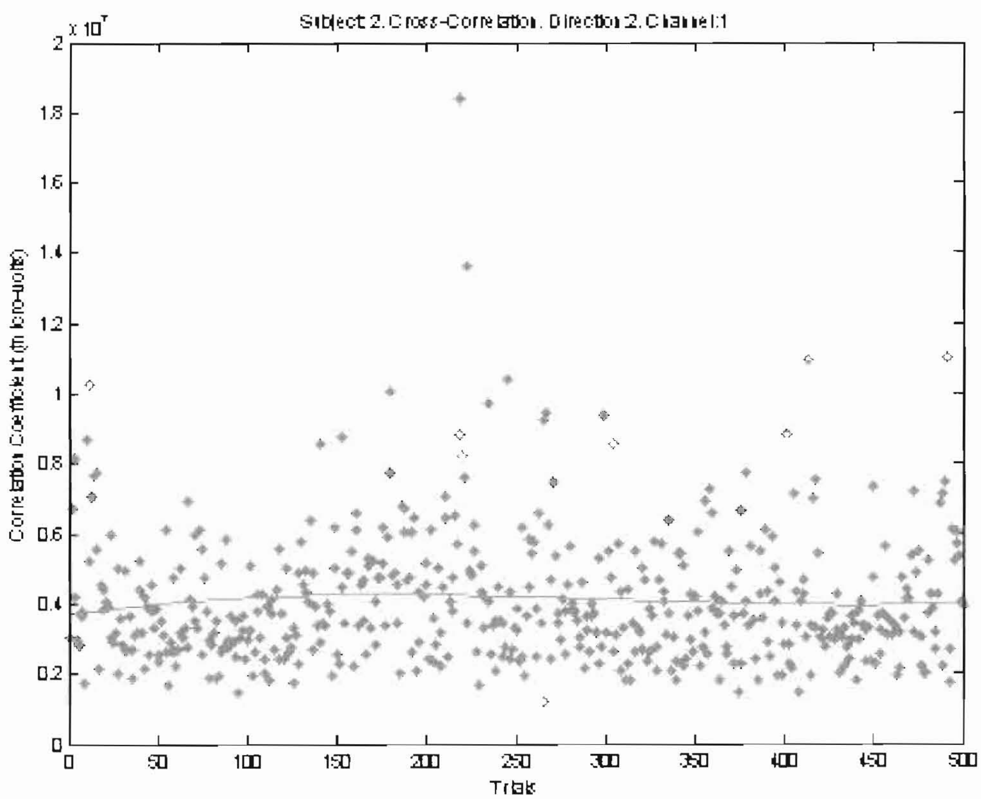

Subject 1. Cross-Correlation. Direction 2. Channel 2
$\times 10^7$
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

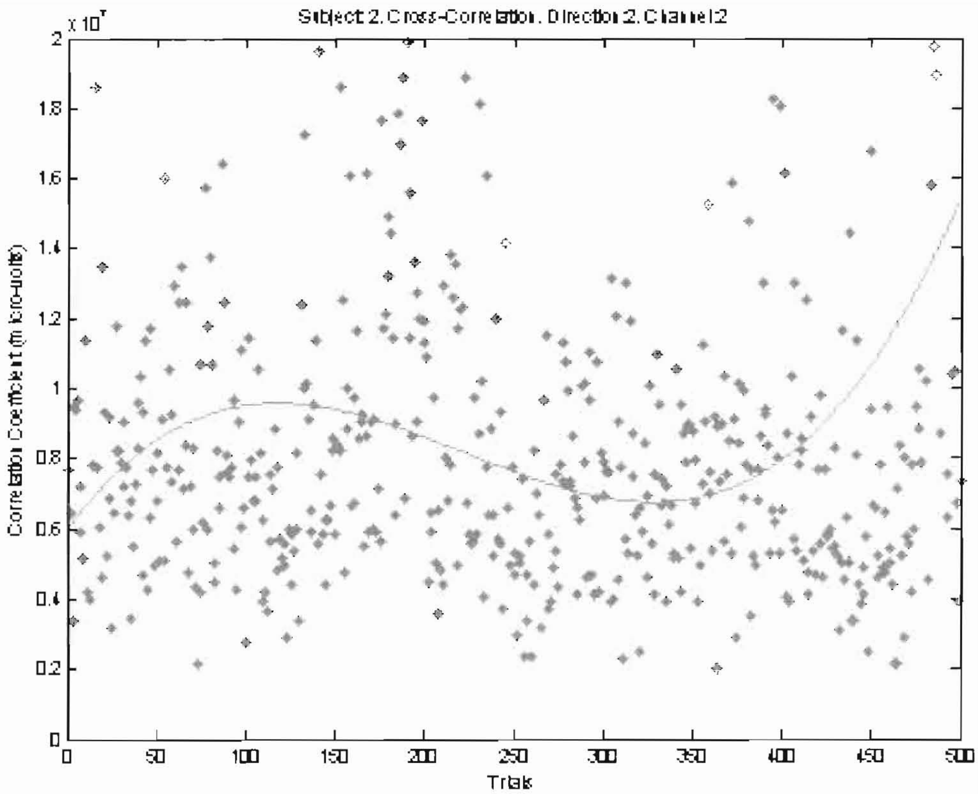

Subject 1. Cross-Correlation. Direction 2. Channel 3
$\times 10^7$
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

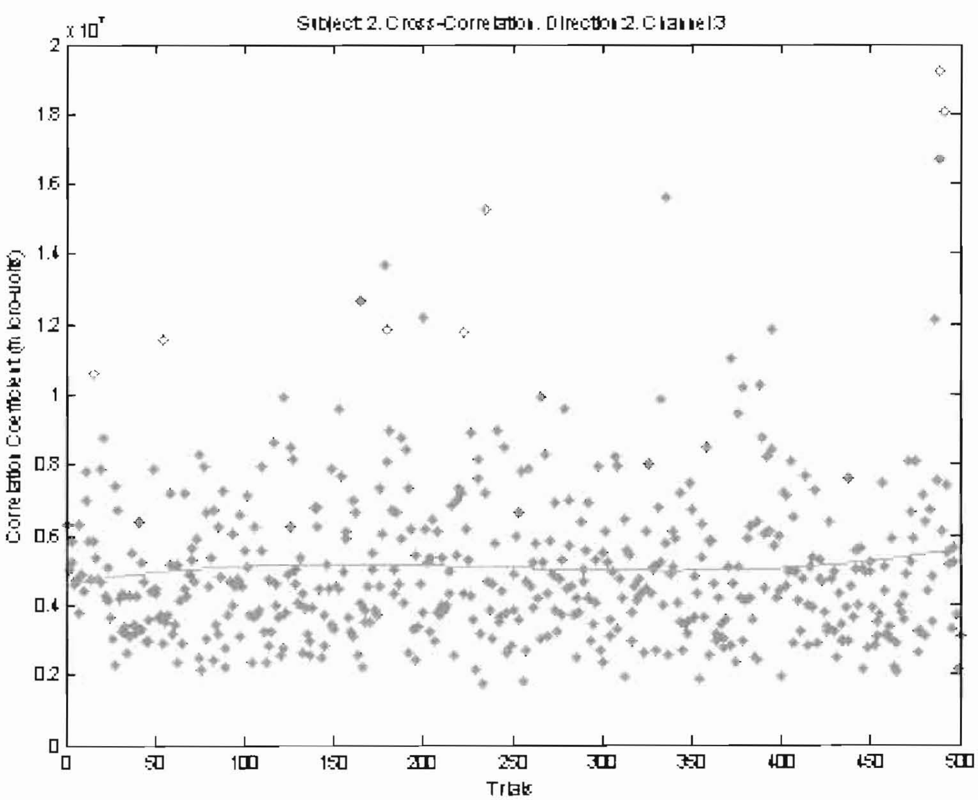

Subject 2. Cross-Correlation. Direction:1. Channel:1
Correlation Coefficient (micro-volts)
Trials

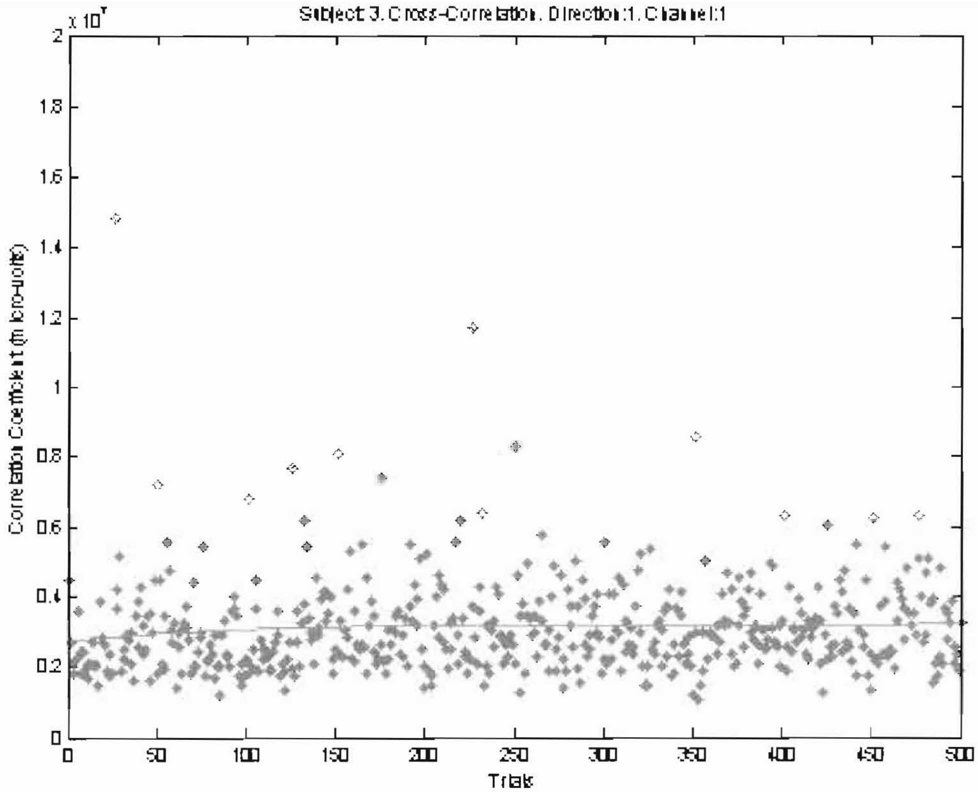

Subject 2. Cross-Correlation. Direction:1. Channel:2
Correlation Coefficient (micro-volts)
Trials


Subject 2. Cross-Correlation. Direction:1. Channel:3
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

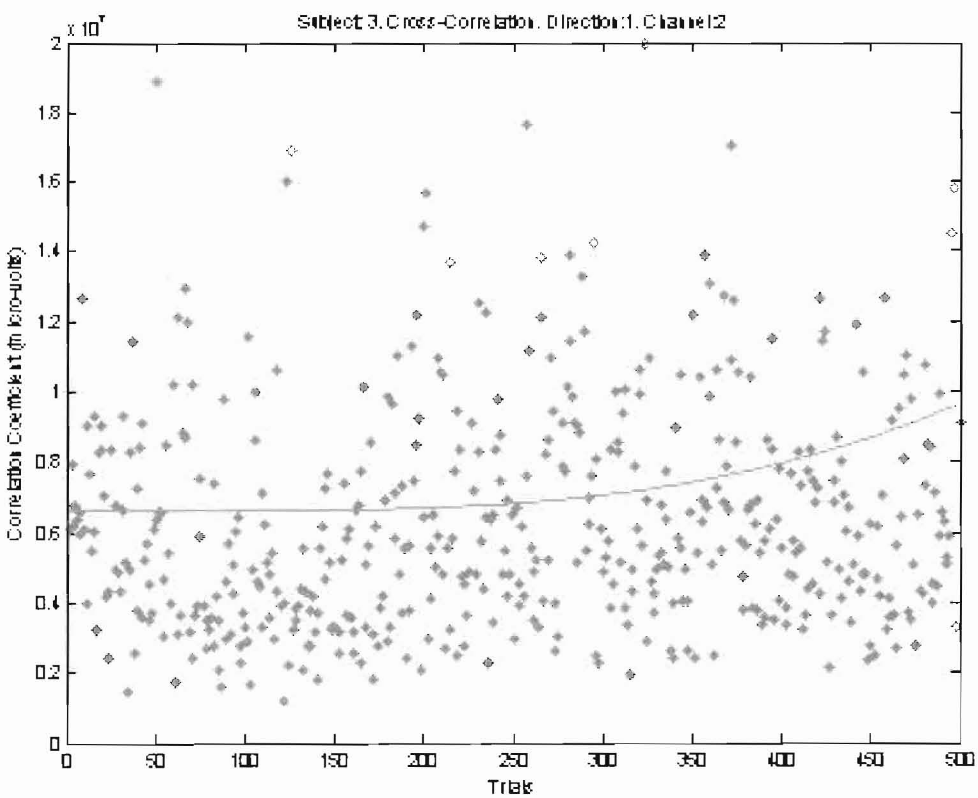

Subject 2. Cross-Correlation. Direction:2. Channel:1
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500


Subject 2, Cross-Correlation, Direction 2, Channel 2
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

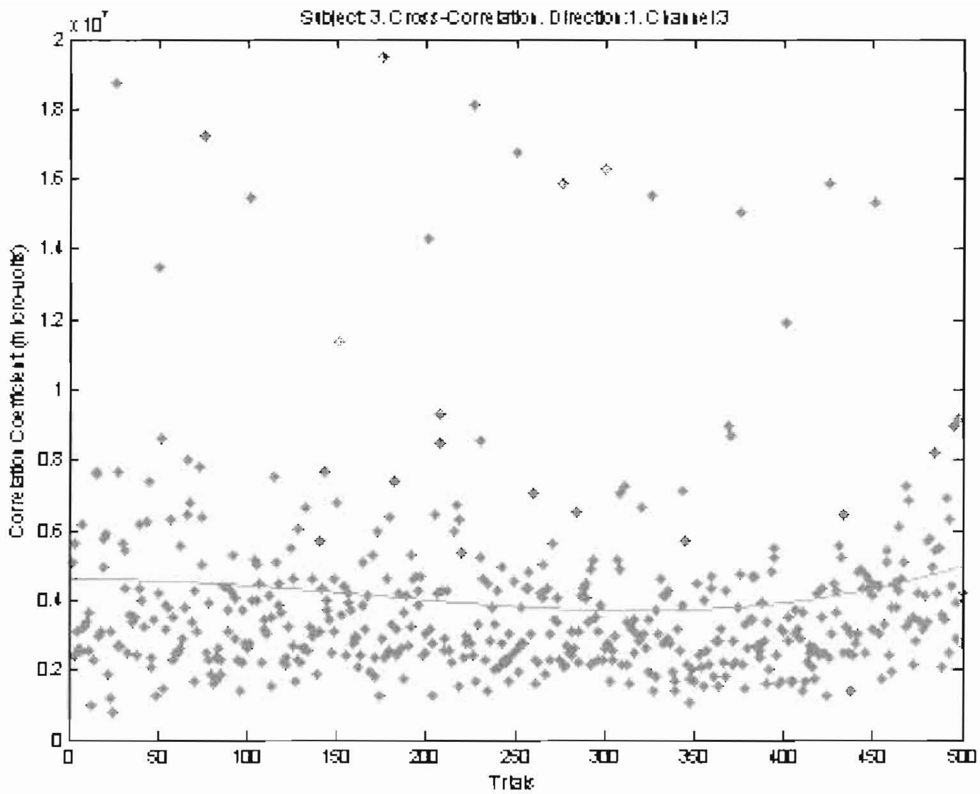

Subject 2, Cross-Correlation, Direction 2, Channel 3
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

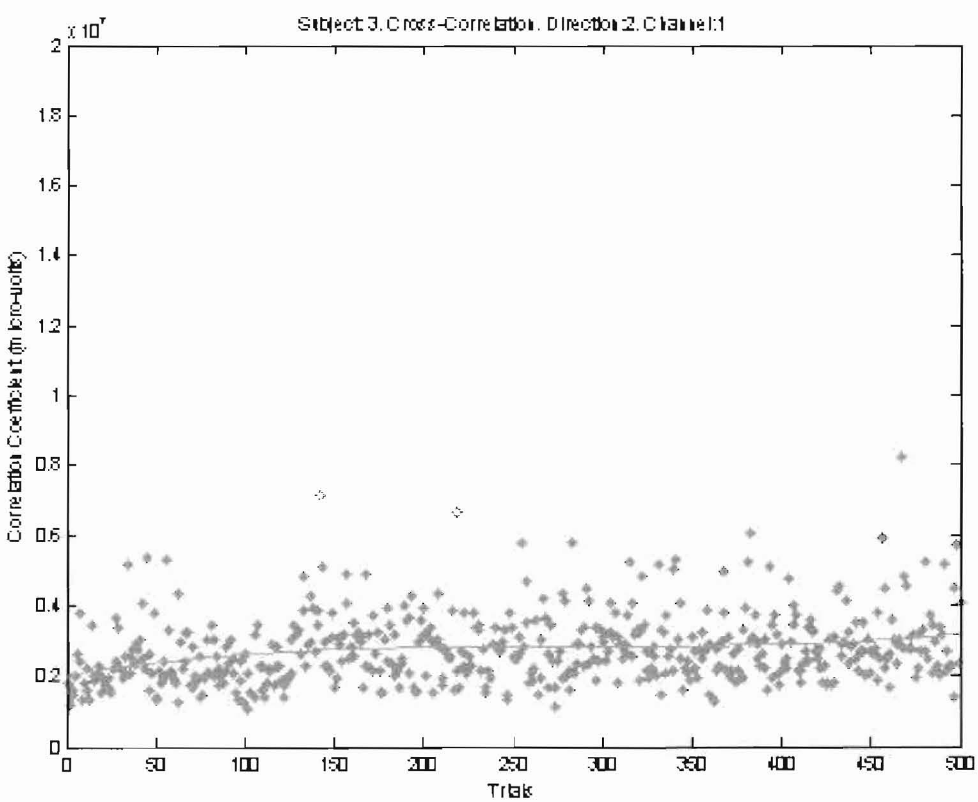


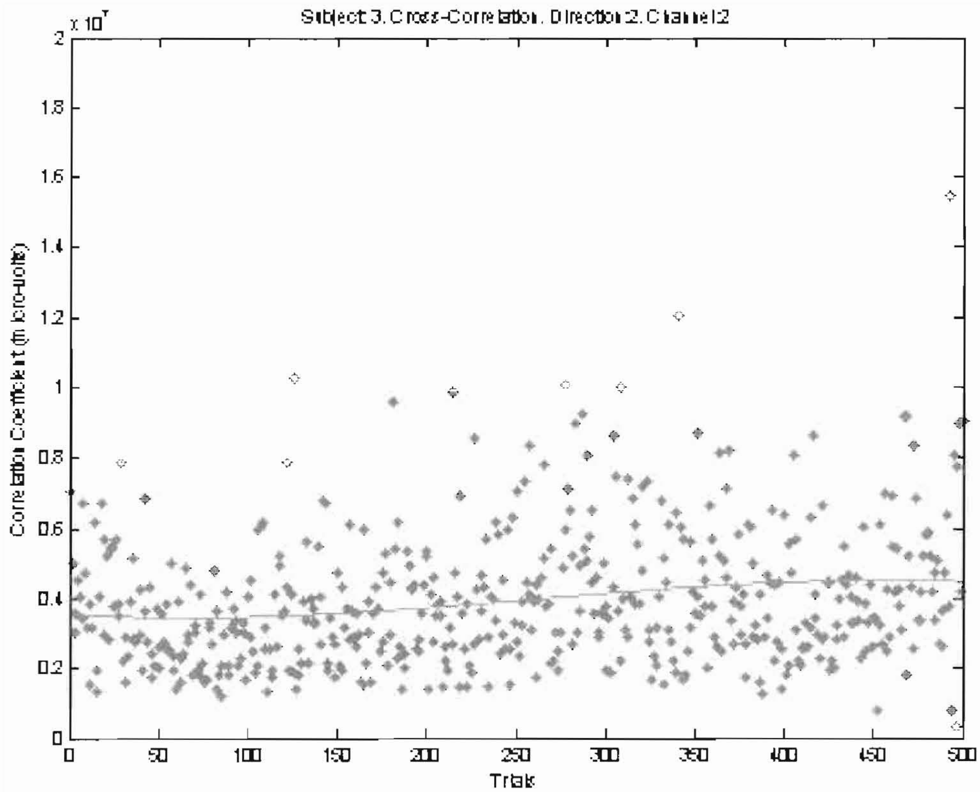
Subject 3. Cross-Correlation. Direction:1. Channel:1
Correlation Coefficient (micro-volts)
Trials

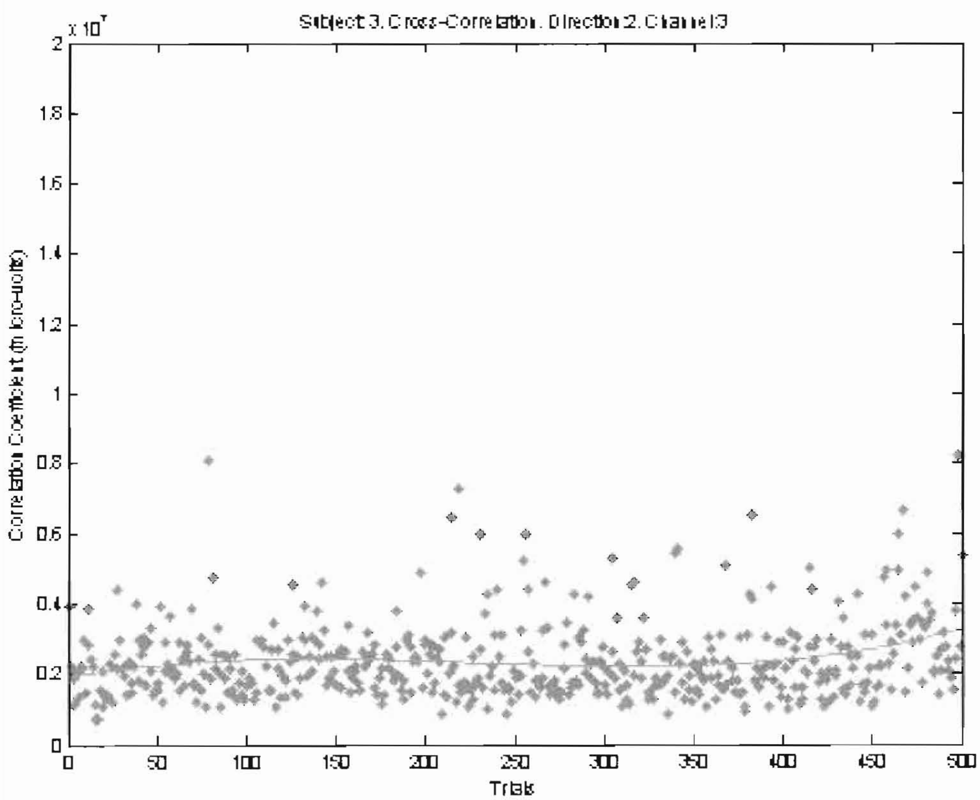


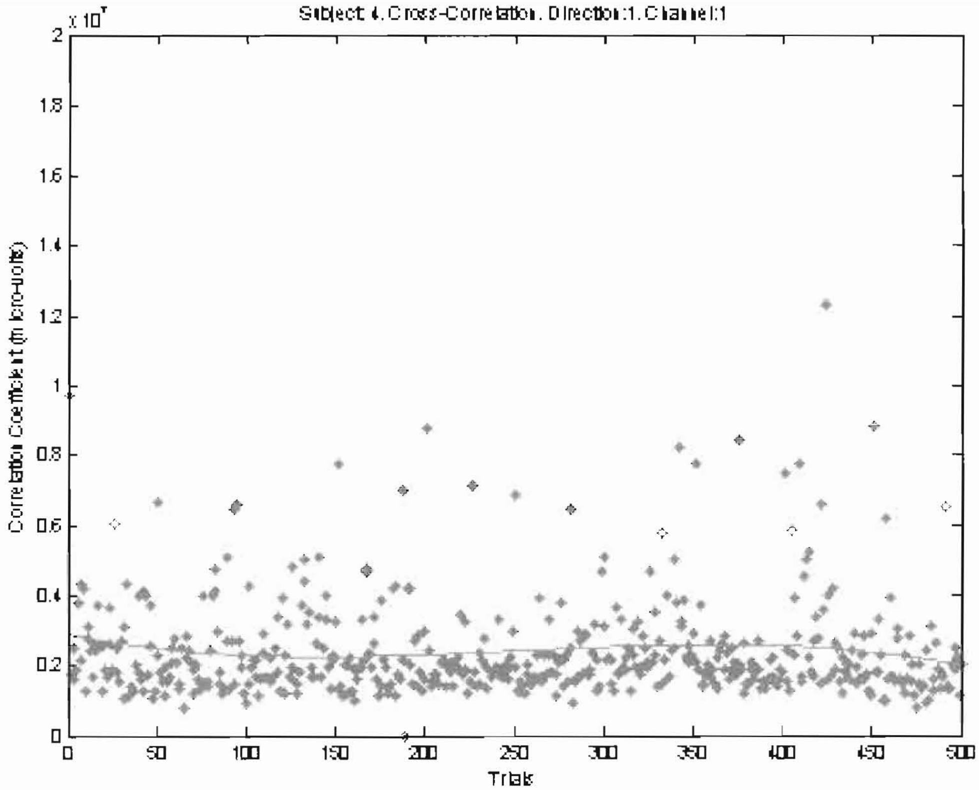
Subject 3. Cross-Correlation. Direction:1. Channel:2
Correlation Coefficient (micro-volts)
Trials

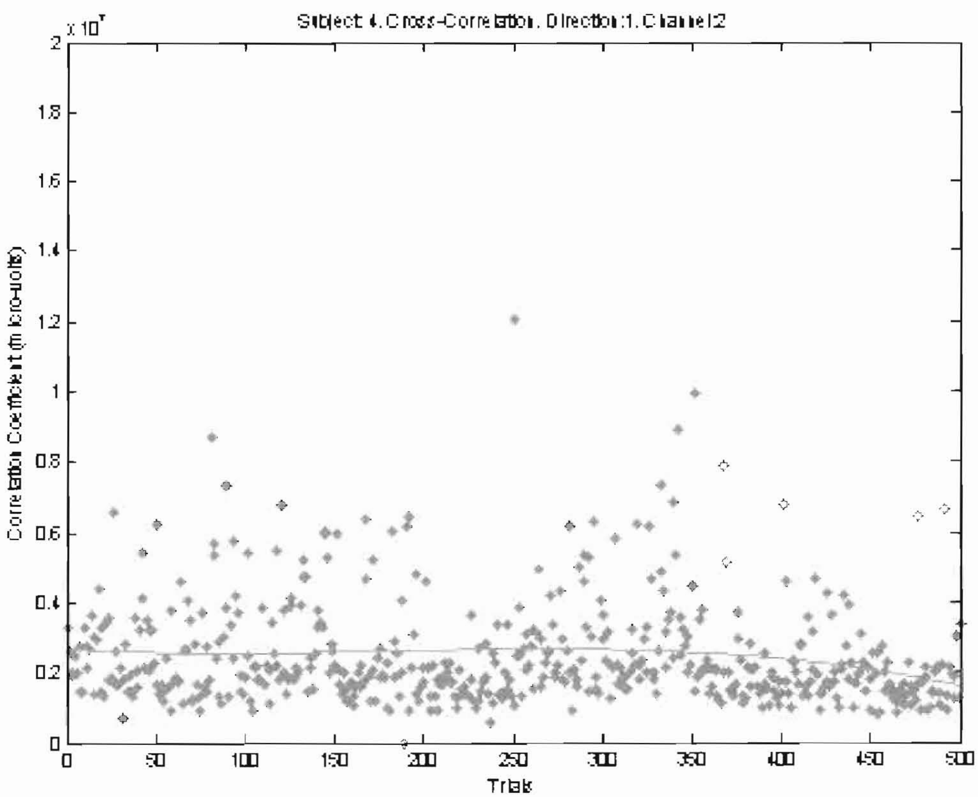

Subject 3. Cross-Correlation. Direction:1. Channel:3
x 10^7
Correlation Coefficient (micro-volts)
Trials

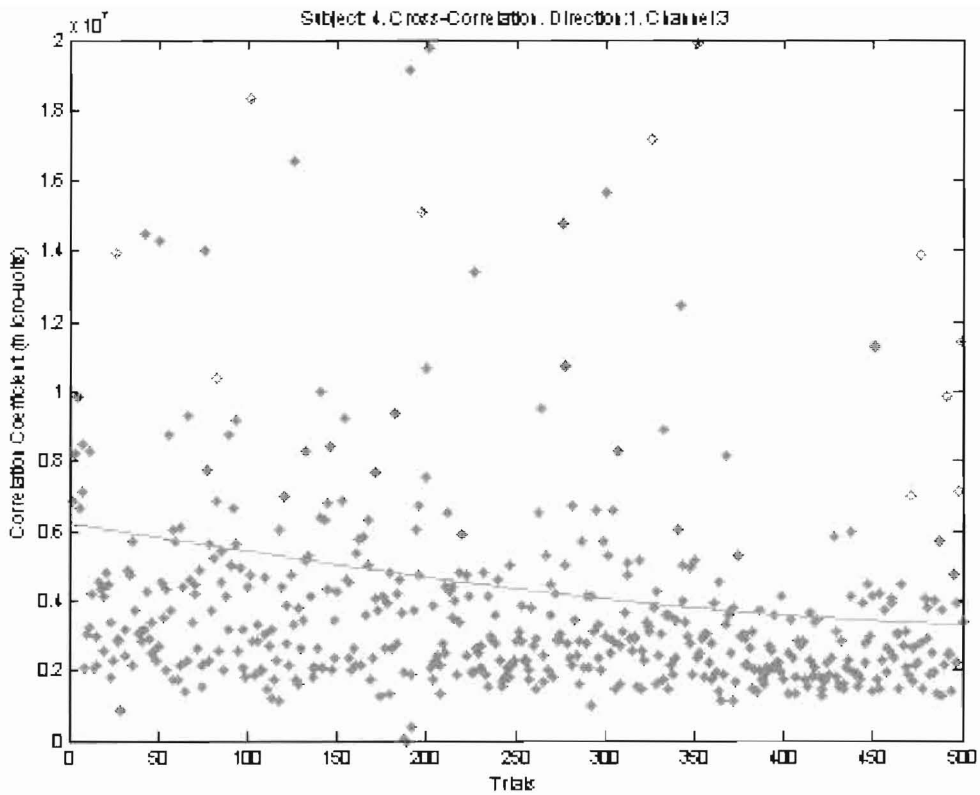

Subject 3. Cross-Correlation. Direction:2. Channel:1
x 10^7
Correlation Coefficient (micro-volts)
Trials

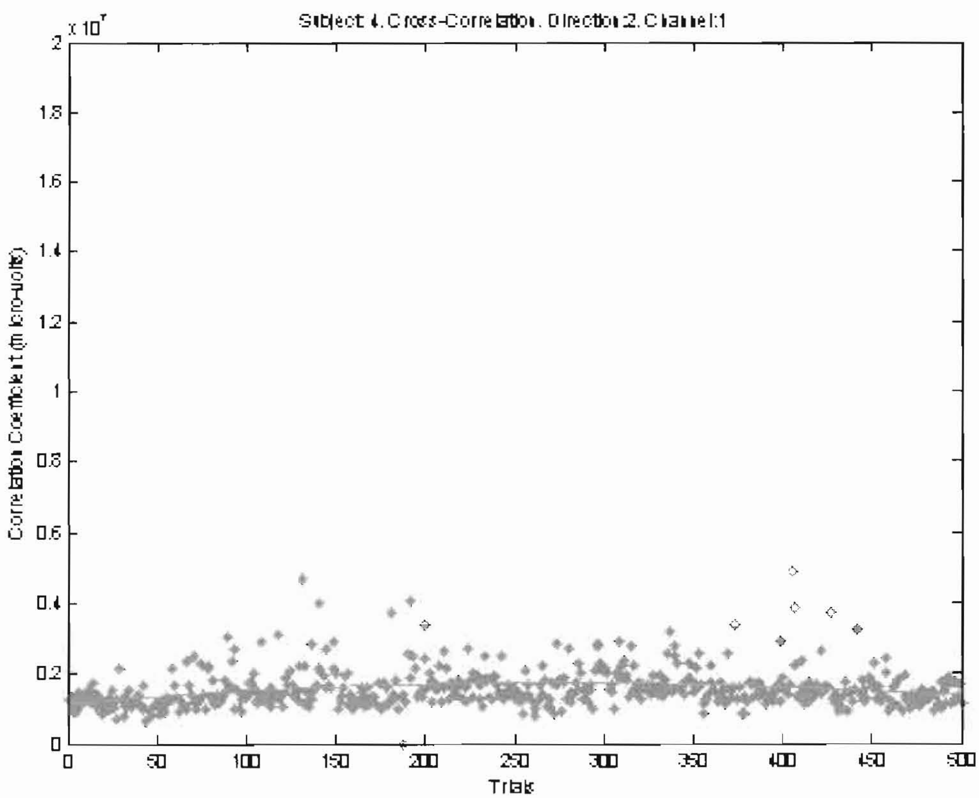

Subject 3, Cross-Correlation, Direction 2, Channel 2
x 10^7
Correlation Coefficient (micro-volts)
Trials

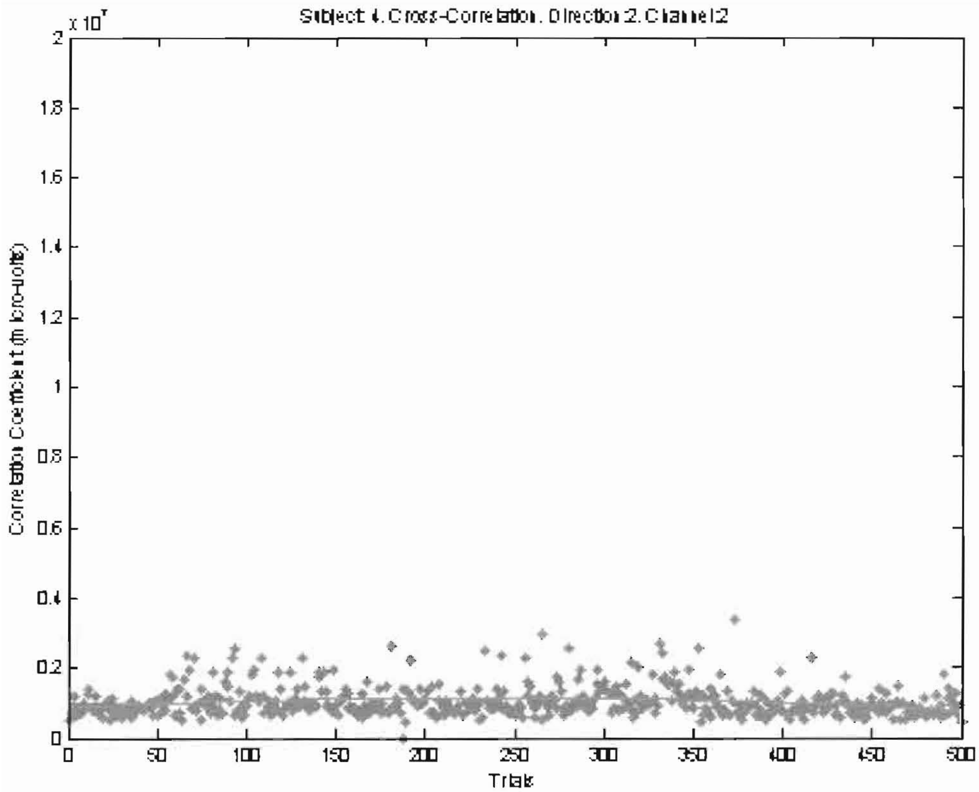

Subject 3, Cross-Correlation, Direction 2, Channel 3
x 10^7
Correlation Coefficient (micro-volts)
Trials

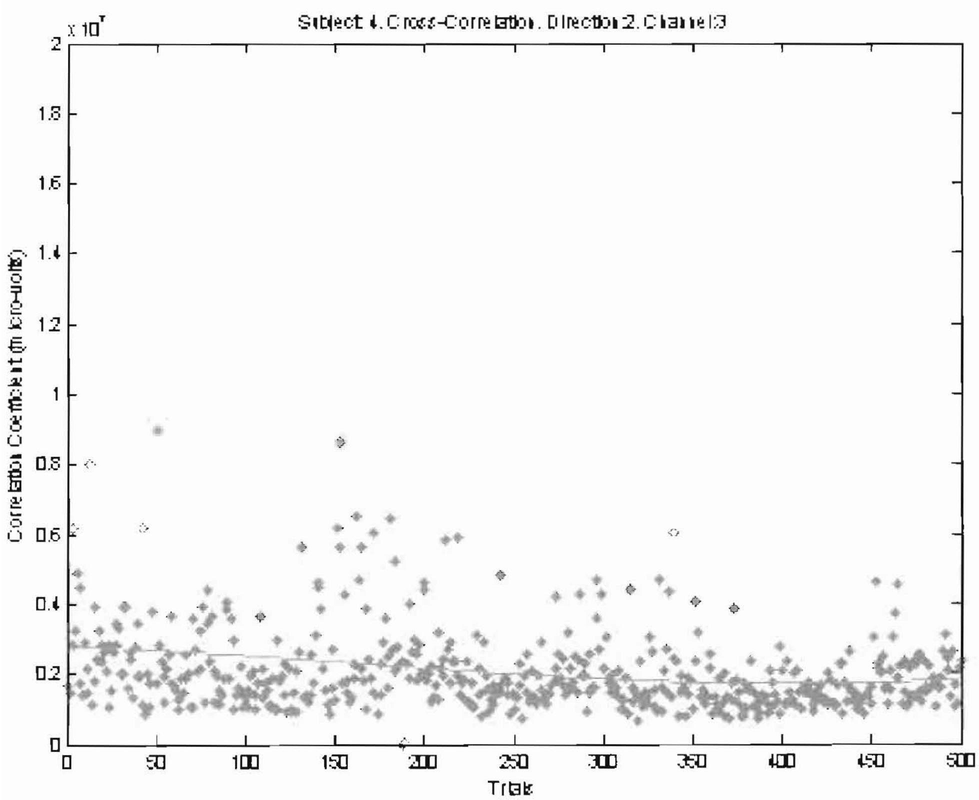

Subject: 4, Cross-Correlation, Direction:1, Channel:1
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
100
150
200
250
300
350
400
450
500

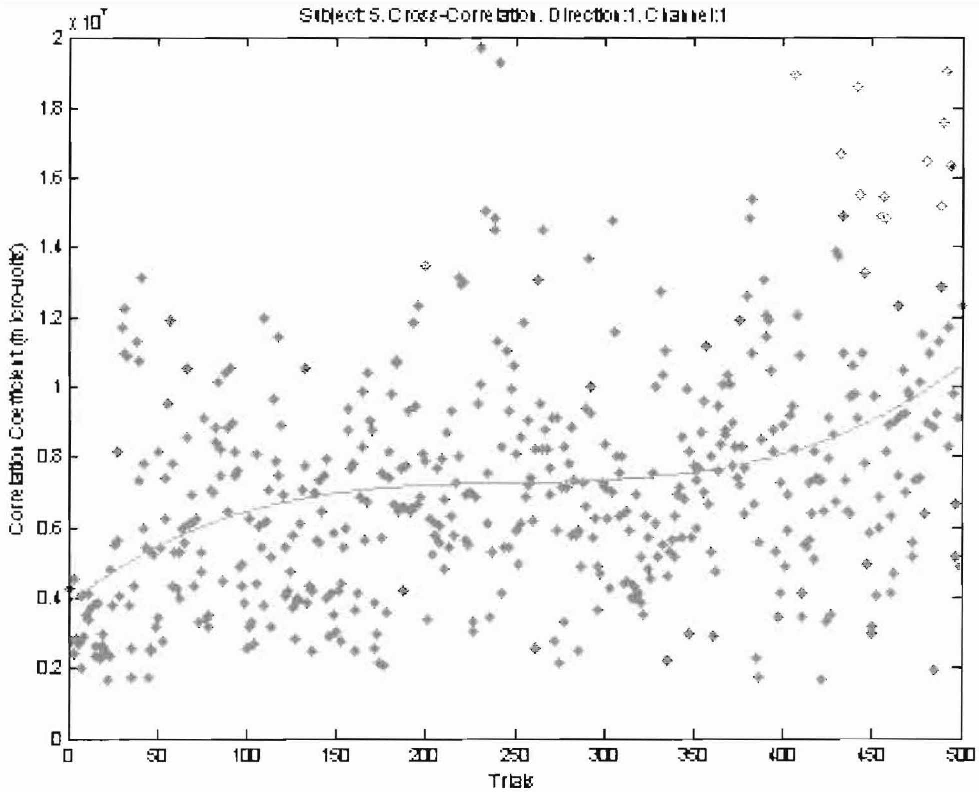

Subject: 4, Cross-Correlation, Direction:1, Channel:2
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
100
150
200
250
300
350
400
450
500

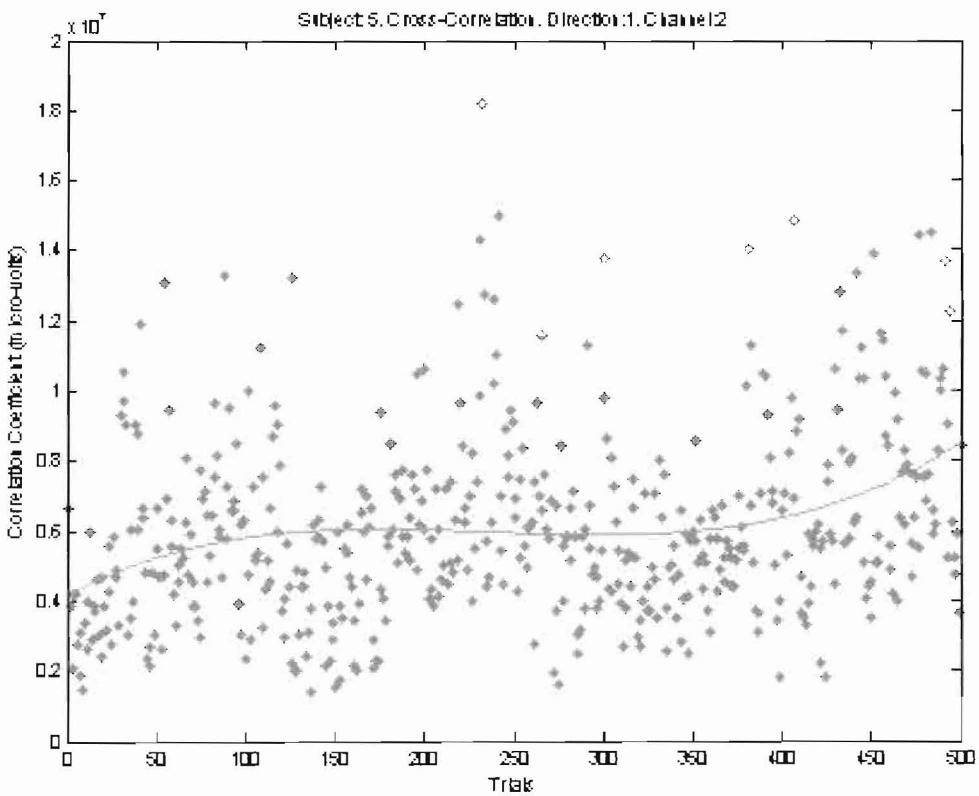

Subject 4, Cross-Correlation, Direction 1, Channel 3
x 10^7
Correlation Coefficient (micro-volts)
Trials

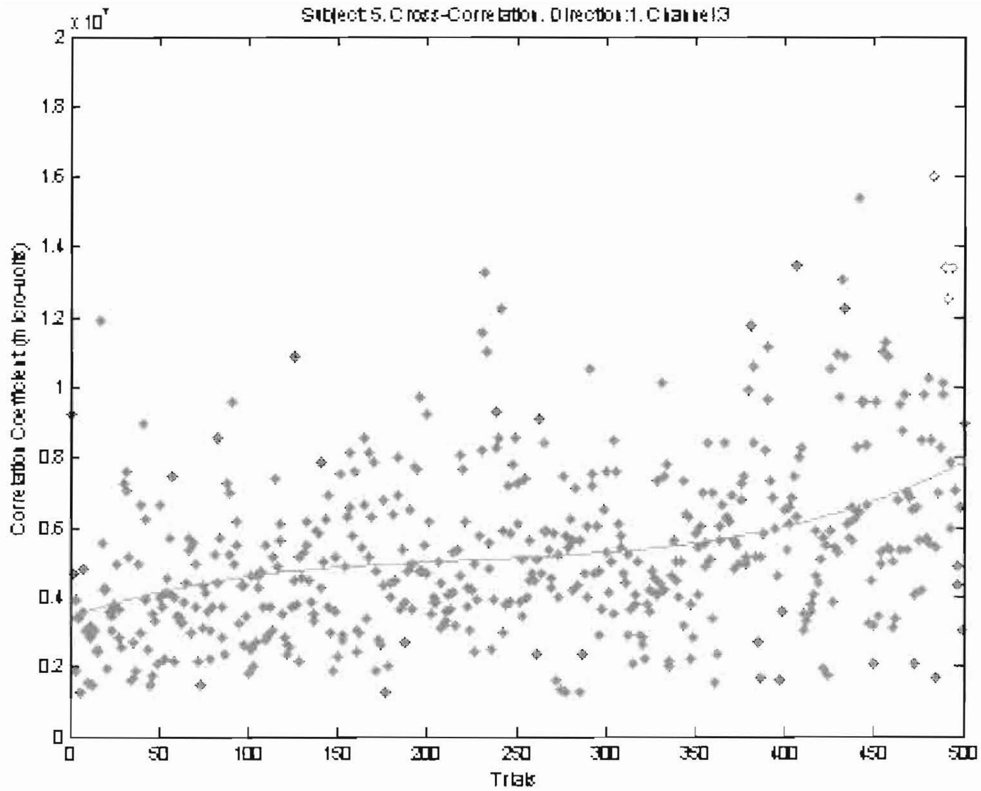

Subject 4, Cross-Correlation, Direction 2, Channel 1
x 10^7
Correlation Coefficient (micro-volts)
Trials

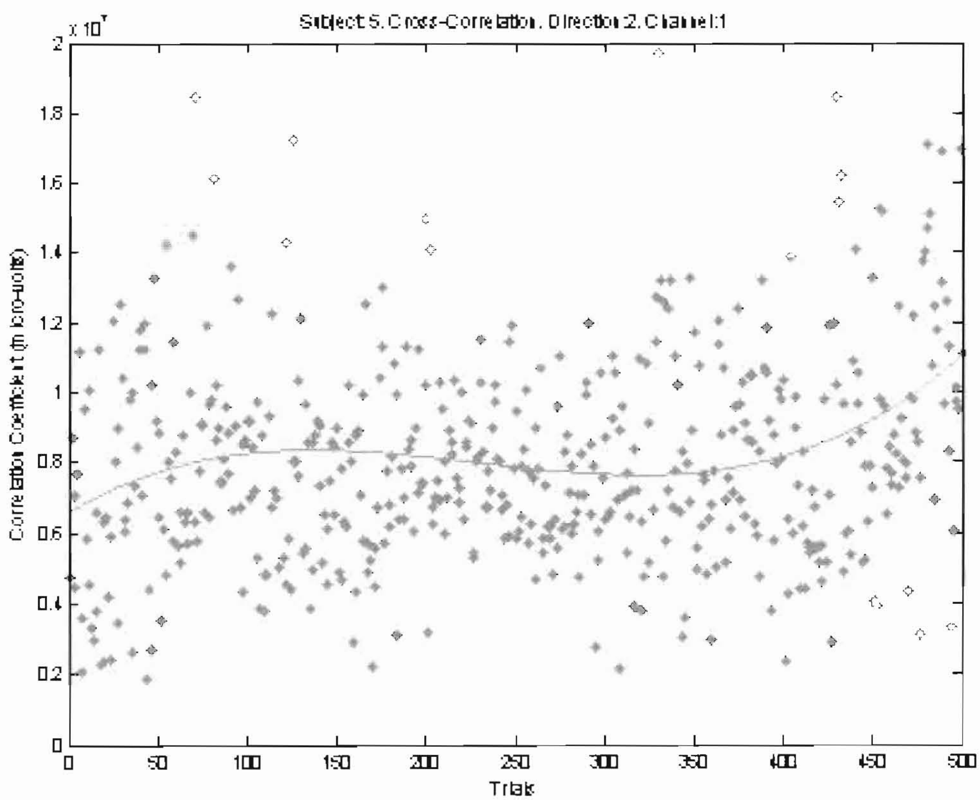

Subject 4. Cross-Correlation. Direction 2. Channel 2
x 10^7
Correlation Coefficient (micro-volts)
Trials

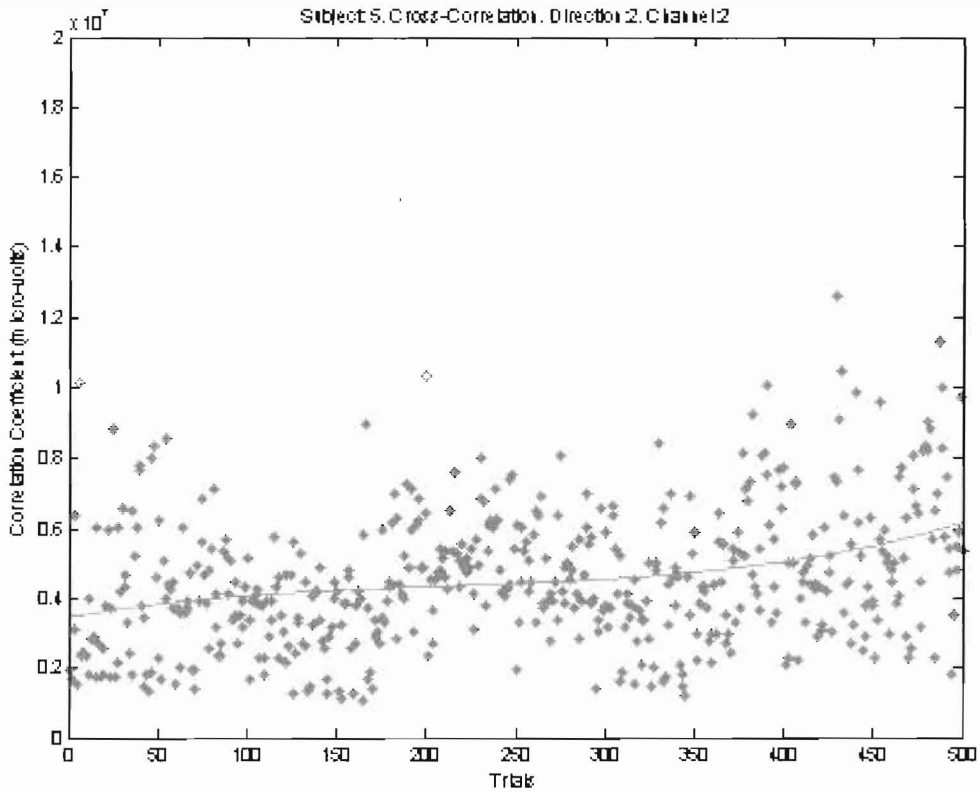

Subject 4. Cross-Correlation. Direction 2. Channel 3
x 10^7
Correlation Coefficient (micro-volts)
Trials

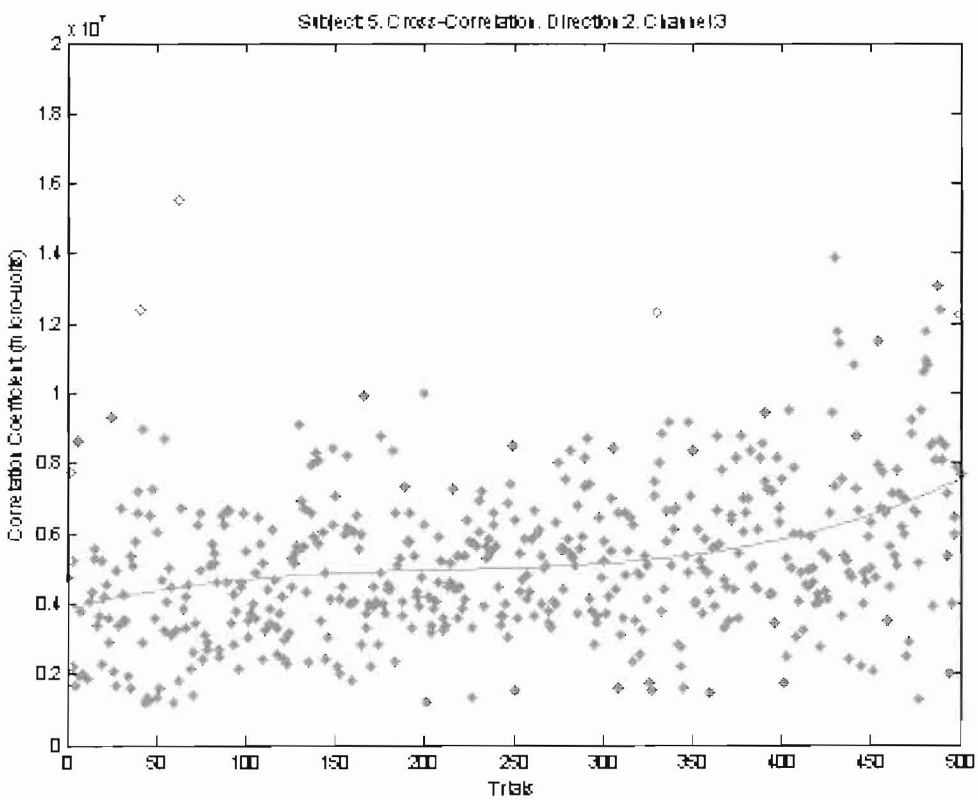

Subject 5. Cross-Correlation. Direction:1. Channel:1
x 10^7
Correlation Coefficient (micro-volts)
Trials
0 50 100 150 200 250 300 350 400 450 500
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2


Subject 5. Cross-Correlation. Direction:1. Channel:2
x 10^7
Correlation Coefficient (micro-volts)
Trials
0 50 100 150 200 250 300 350 400 450 500
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

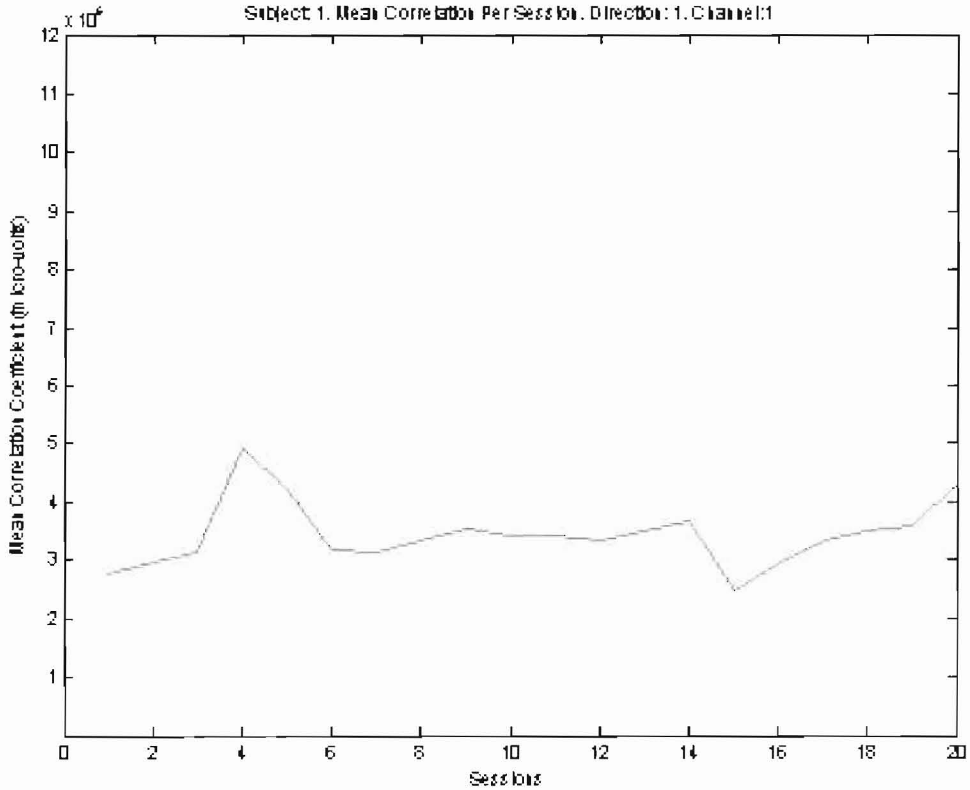

Subject 5. Cross-Correlation. Direction:1. Channel:3
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

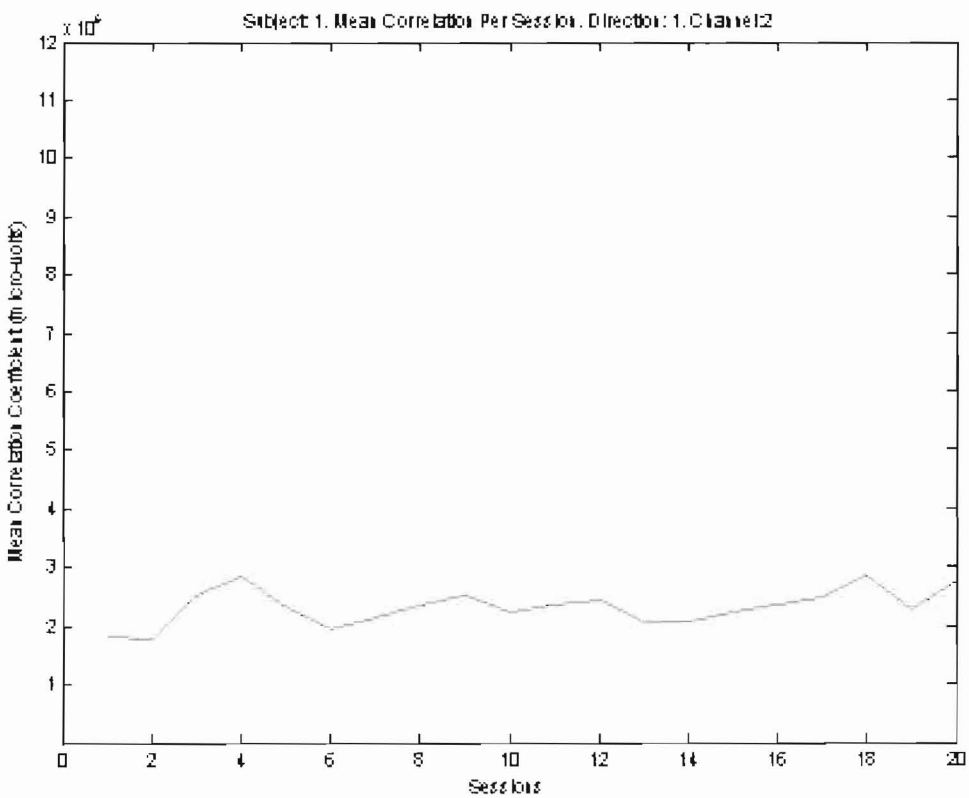

Subject 5. Cross-Correlation. Direction:2. Channel:1
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
350
400
450
500

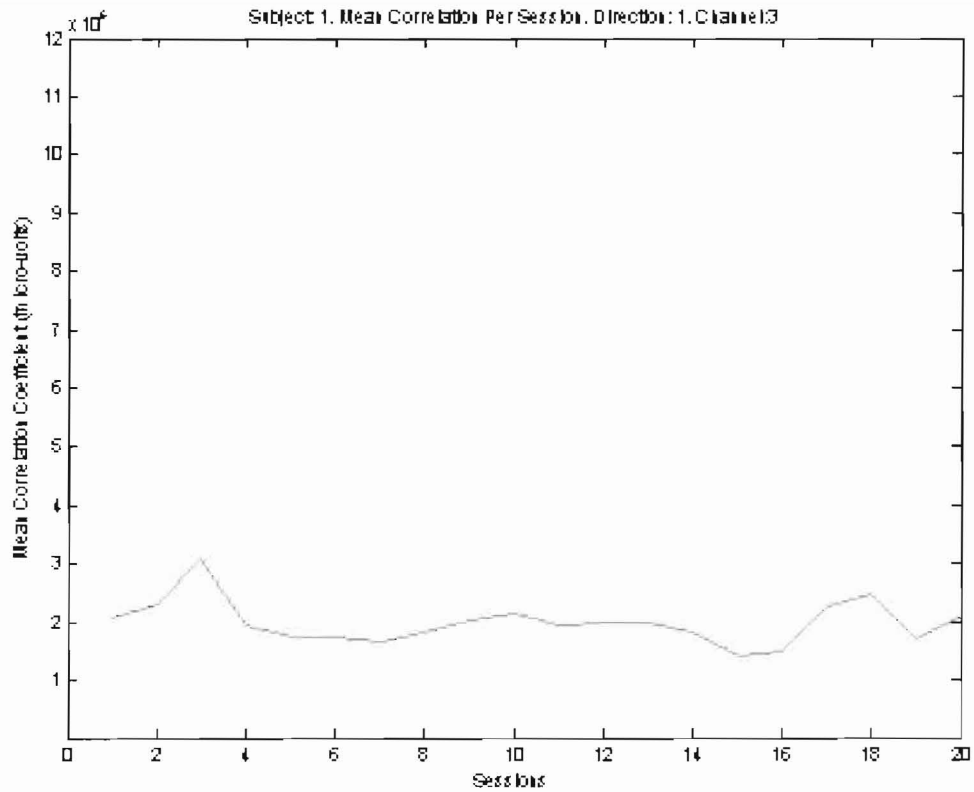

Subject 5. Cross-Correlation. Direction 2. Channel 2
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
100
150
200
250
300
350
400
450
500

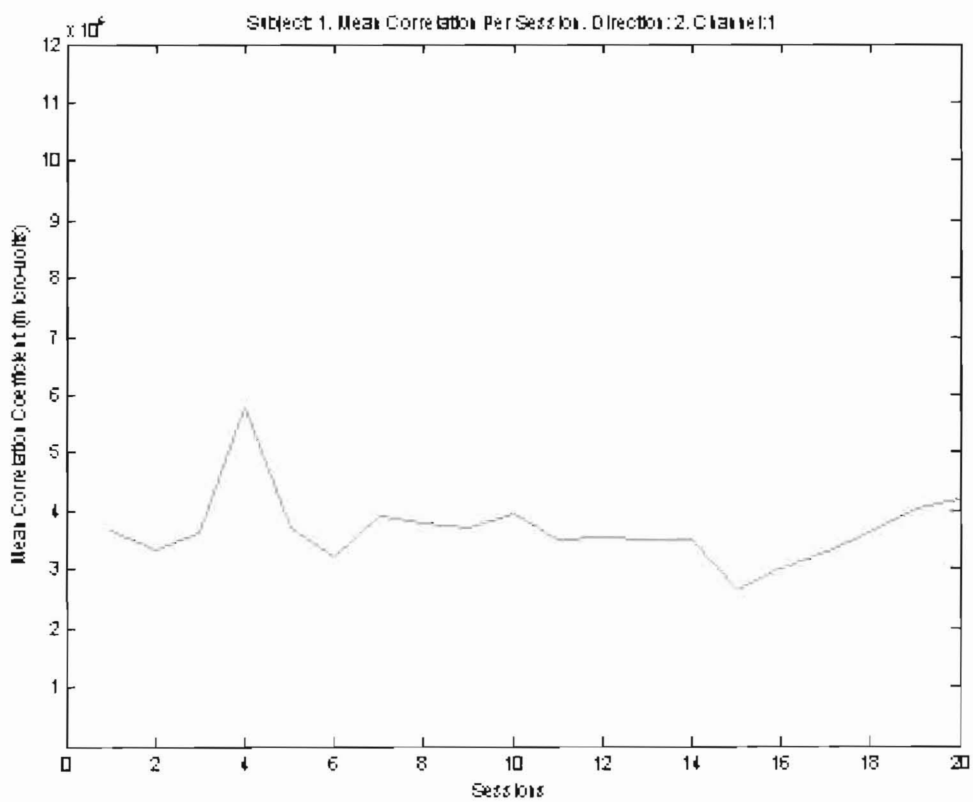

Subject 5. Cross-Correlation. Direction 2. Channel 3
x 10^7
Correlation Coefficient (micro-volts)
Trials
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
100
150
200
250
300
350
400
450
500

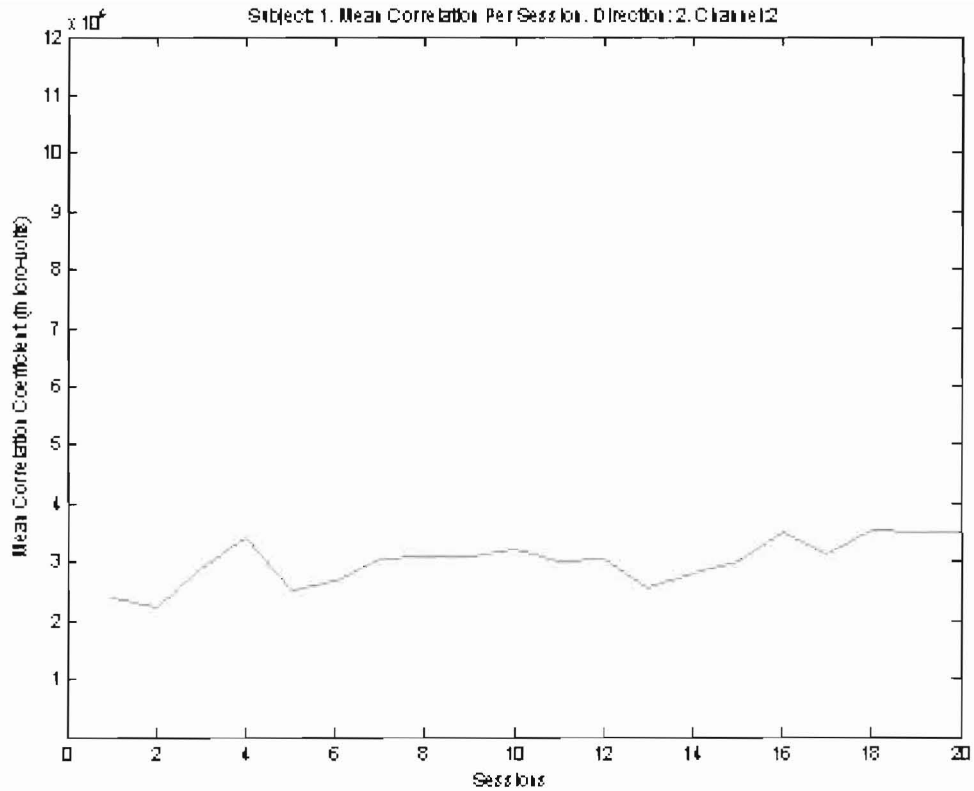
APPENDIX 6: MEAN CORRELATION COEFFICIENTS PER SESSION RESULTS

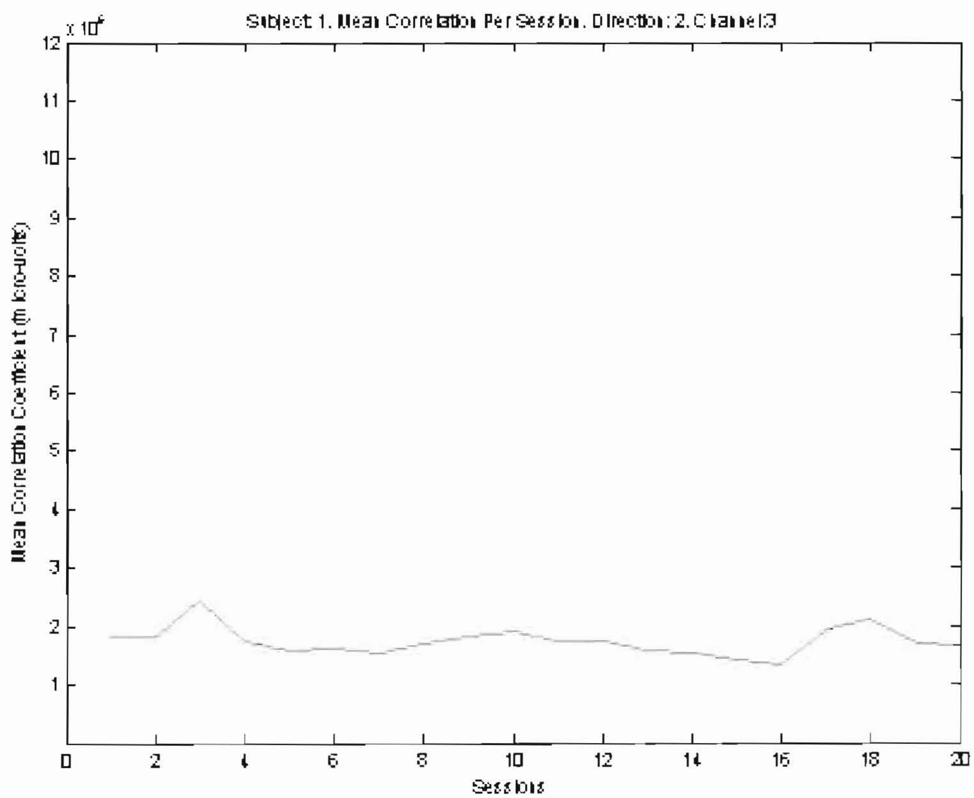

Subject: 1. Mean Correlation Per Session. Direction: 1. Channel:1
Mean Correlation Coefficient (micro-volts)
Sessions

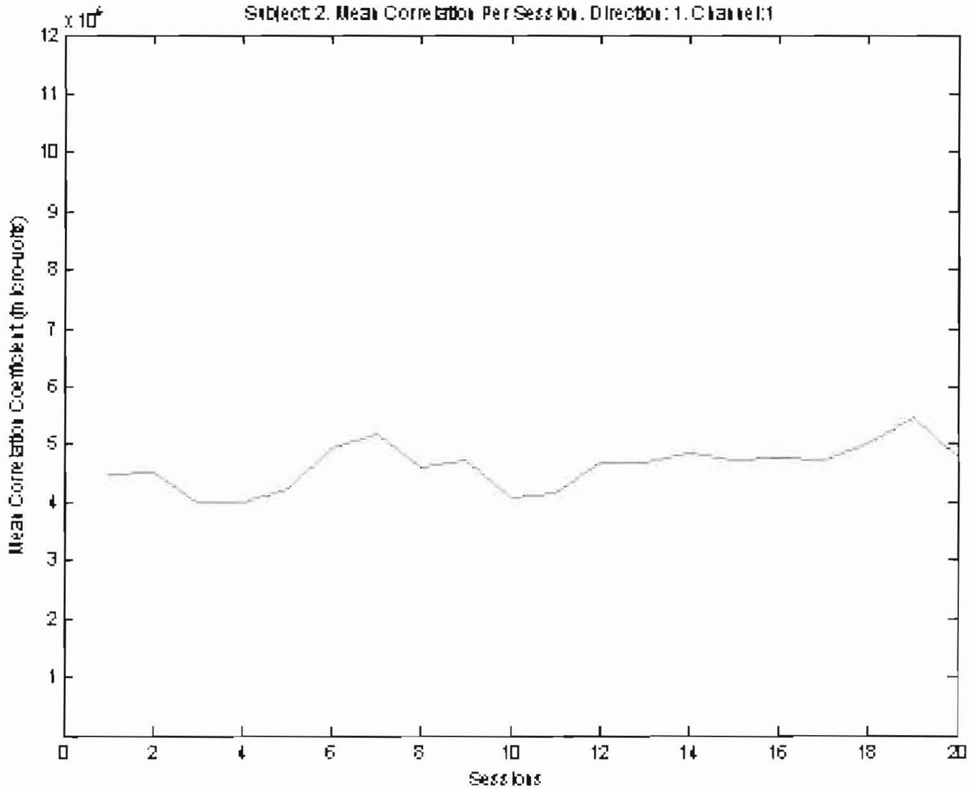

Subject: 1. Mean Correlation Per Session. Direction: 1. Channel:2
Mean Correlation Coefficient (micro-volts)
Sessions


Subject: 1. Mean Correlation Per Session. Direction: 1. Channel:3
Mean Correlation Coefficient (micro-volts)
Sessions

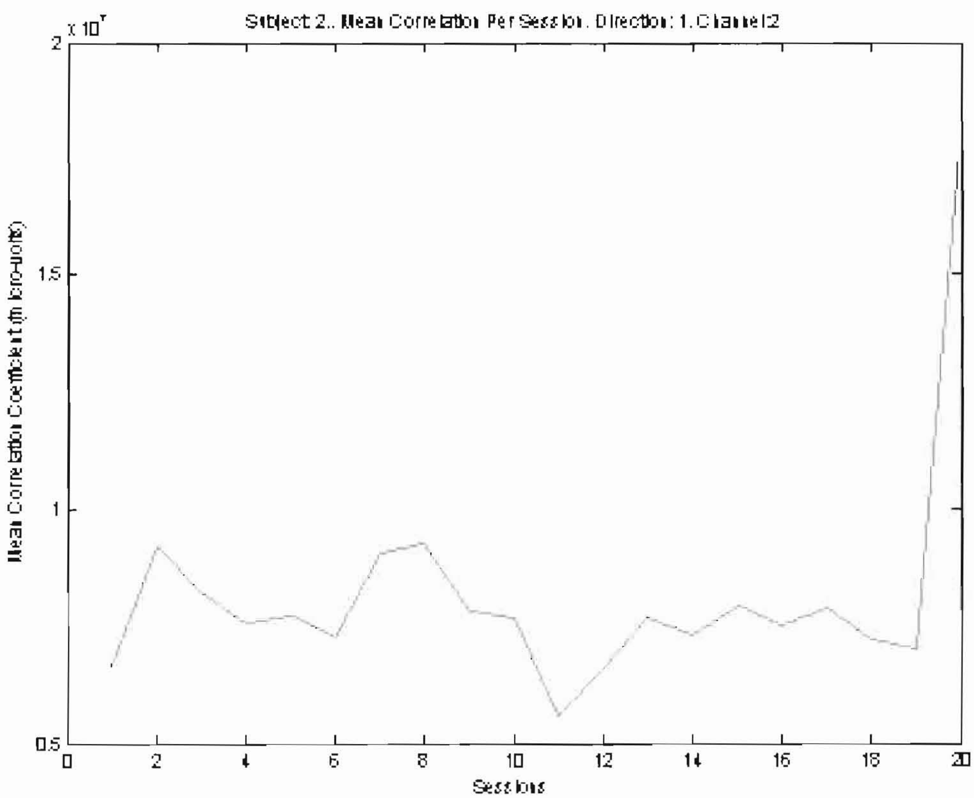

Subject: 1. Mean Correlation Per Session. Direction: 2. Channel:1
Mean Correlation Coefficient (micro-volts)
Sessions


Subject: 1. Mean Correlation Per Session. Direction: 2. Channel:2
x 10^-4
Mean Correlation Coefficient (micro-volts)
Sessions

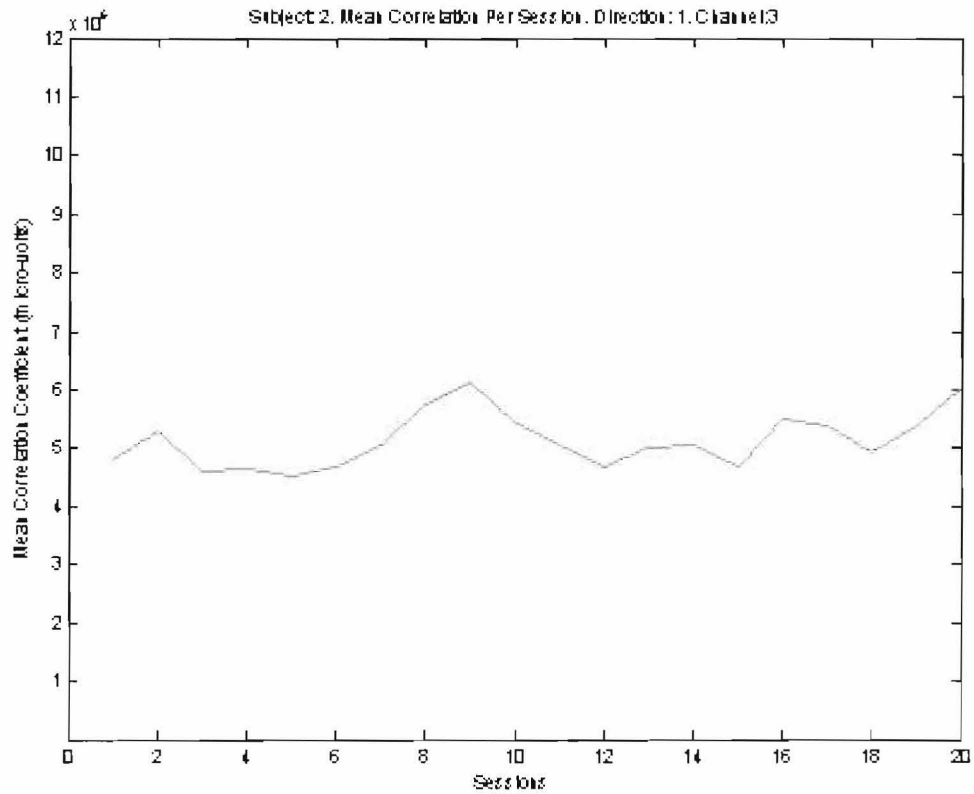

Subject: 1. Mean Correlation Per Session. Direction: 2. Channel:3
x 10^-4
Mean Correlation Coefficient (micro-volts)
Sessions

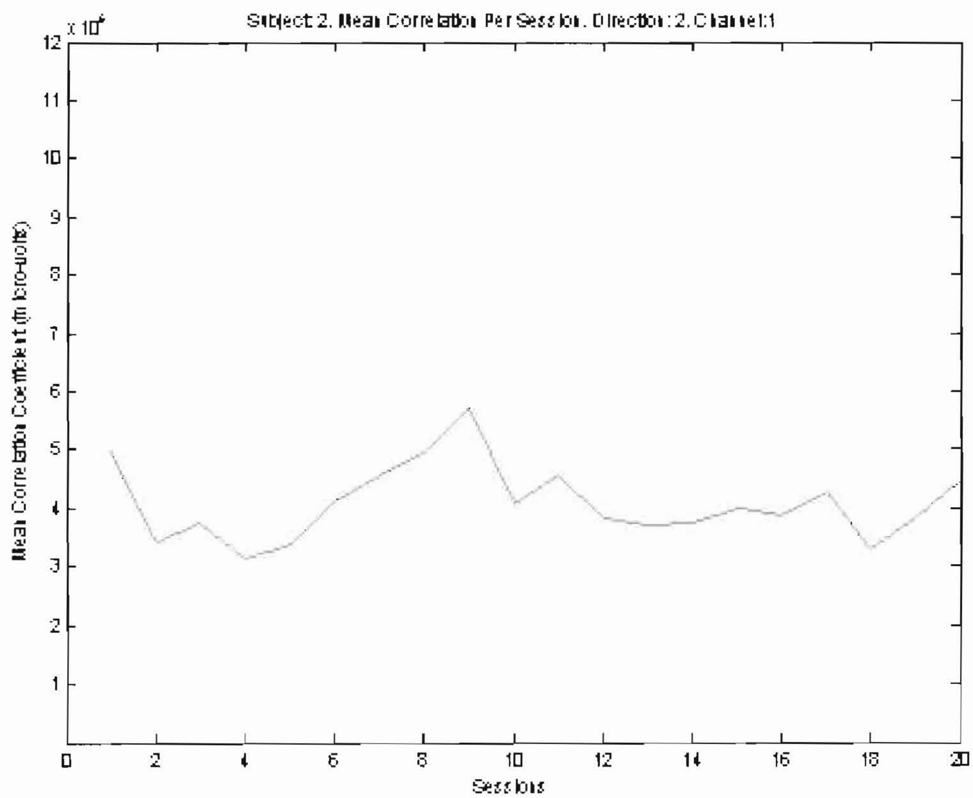


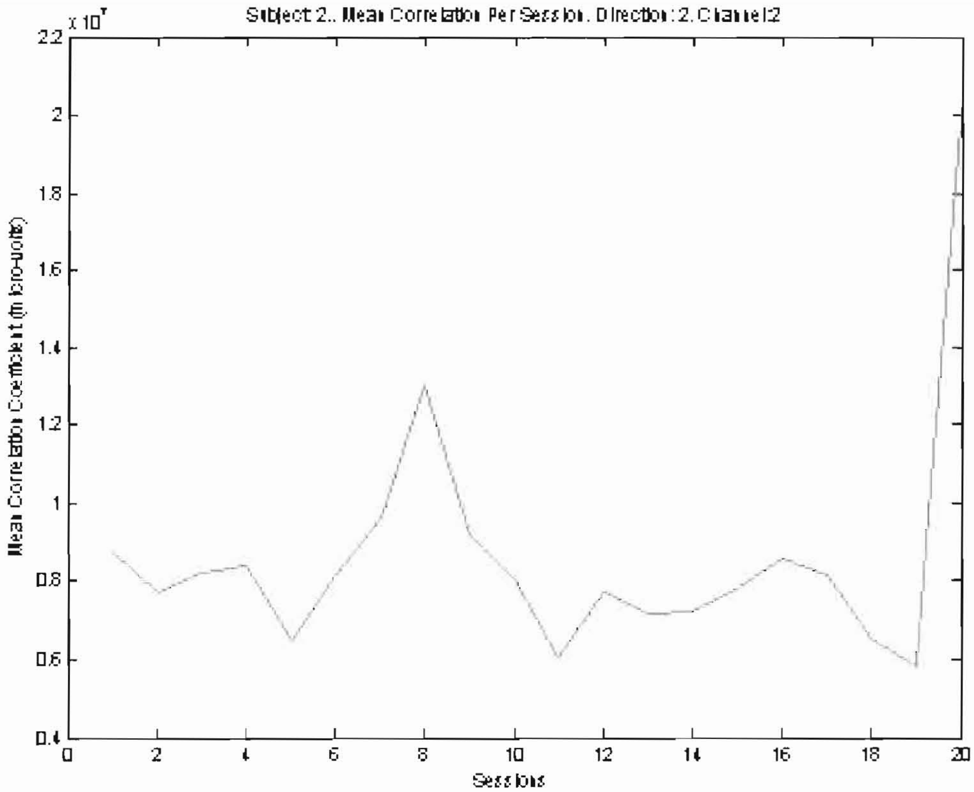
Subject 2. Mean Correlation Per Session. Direction: 1. Channel:1
x 10^-4
Mean Correlation Coefficient (micro-volts)
Sessions

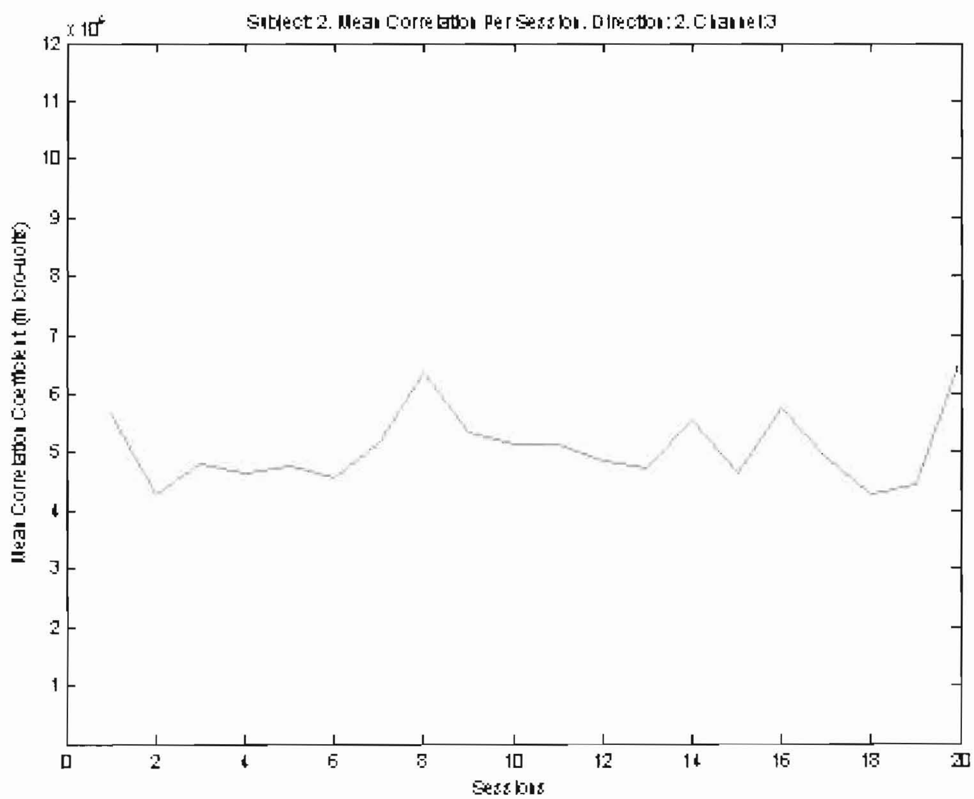


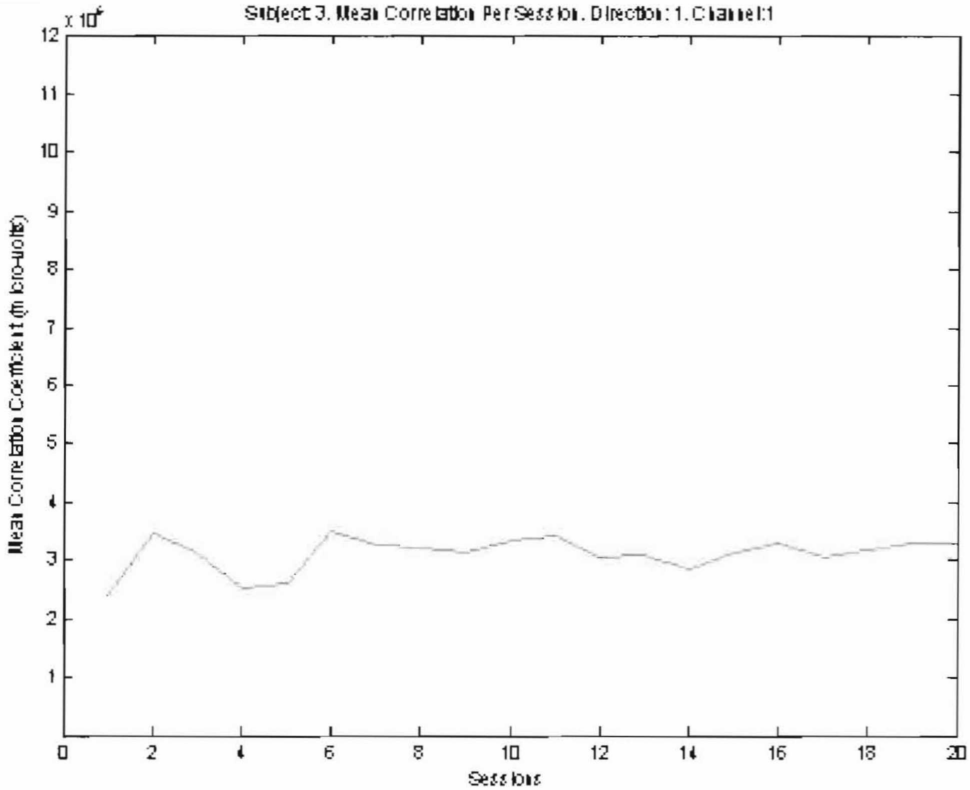
Subject 2.. Mean Correlation Per Session. Direction: 1. Channel:2
x 10^-7
Mean Correlation Coefficient (micro-volts)
Sessions

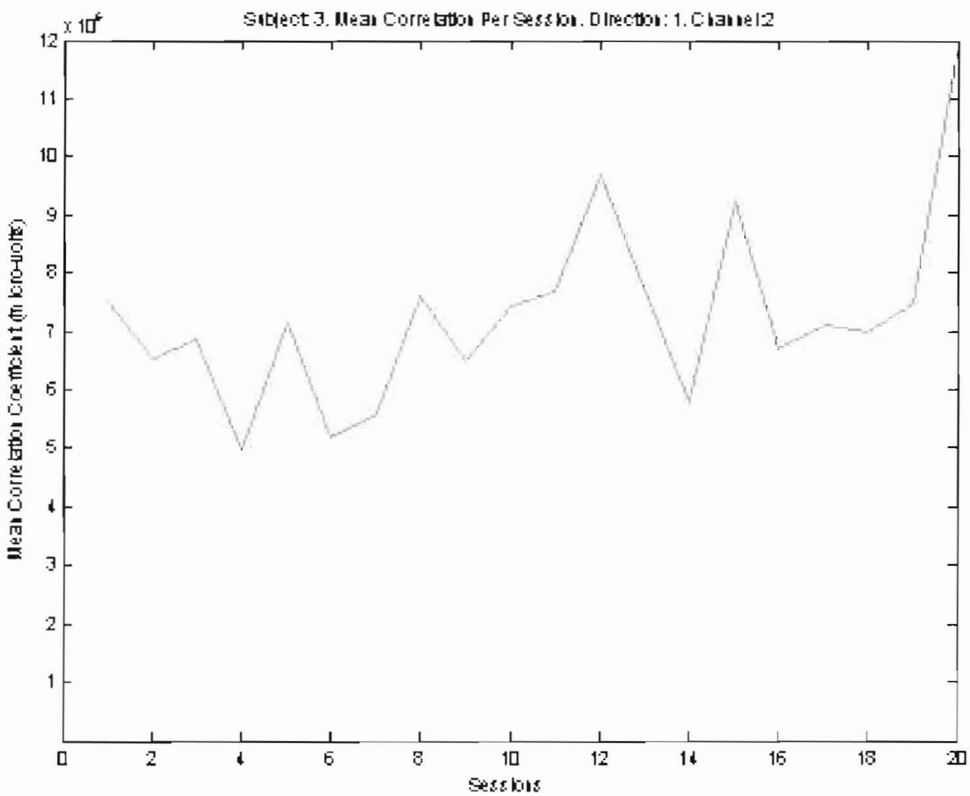

Subject: 2. Mean Correlation Per Session. Direction: 1. Channel:3
x 10^4
Mean Correlation Coefficient (micro-volts)
Sessions

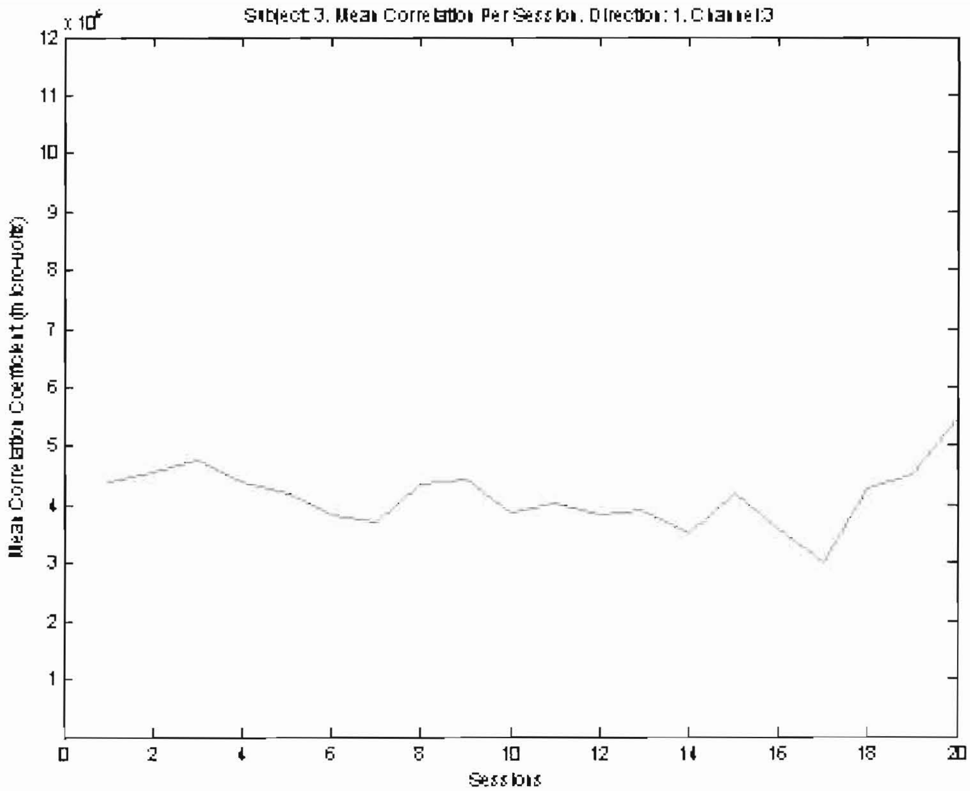

Subject: 2. Mean Correlation Per Session. Direction: 2. Channel:1
x 10^4
Mean Correlation Coefficient (micro-volts)
Sessions

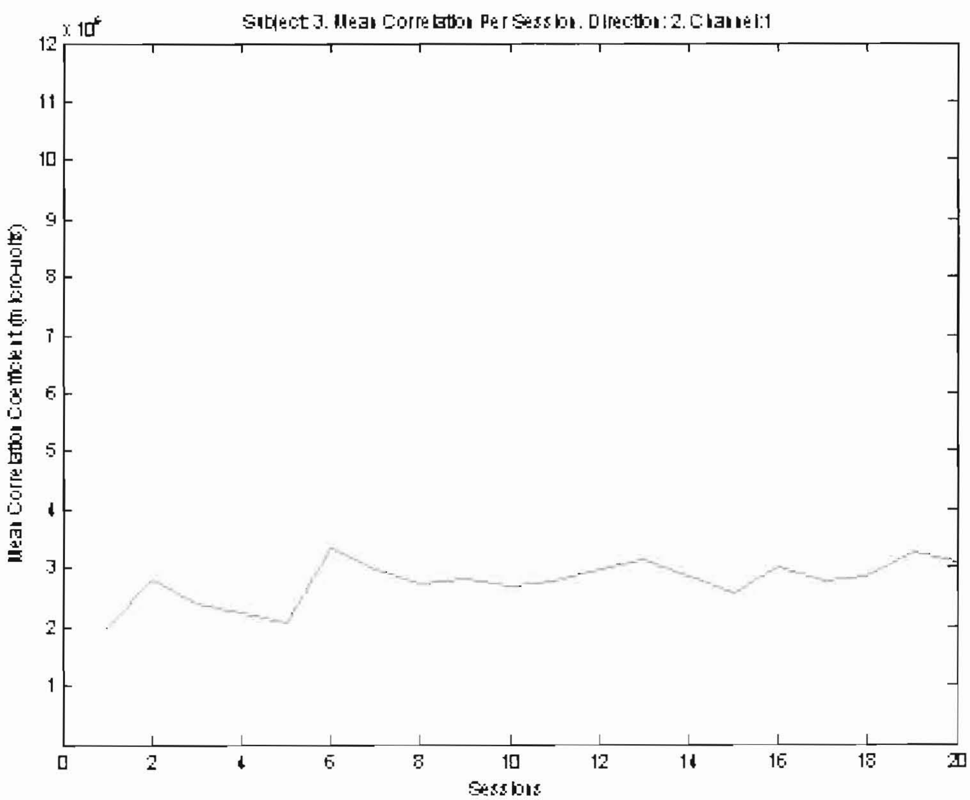

Subject: 2.. Mean Correlation Per Session. Direction: 2. Channel:2
x 10^7
Mean Correlation Coefficient (micro-volts)
Sessions

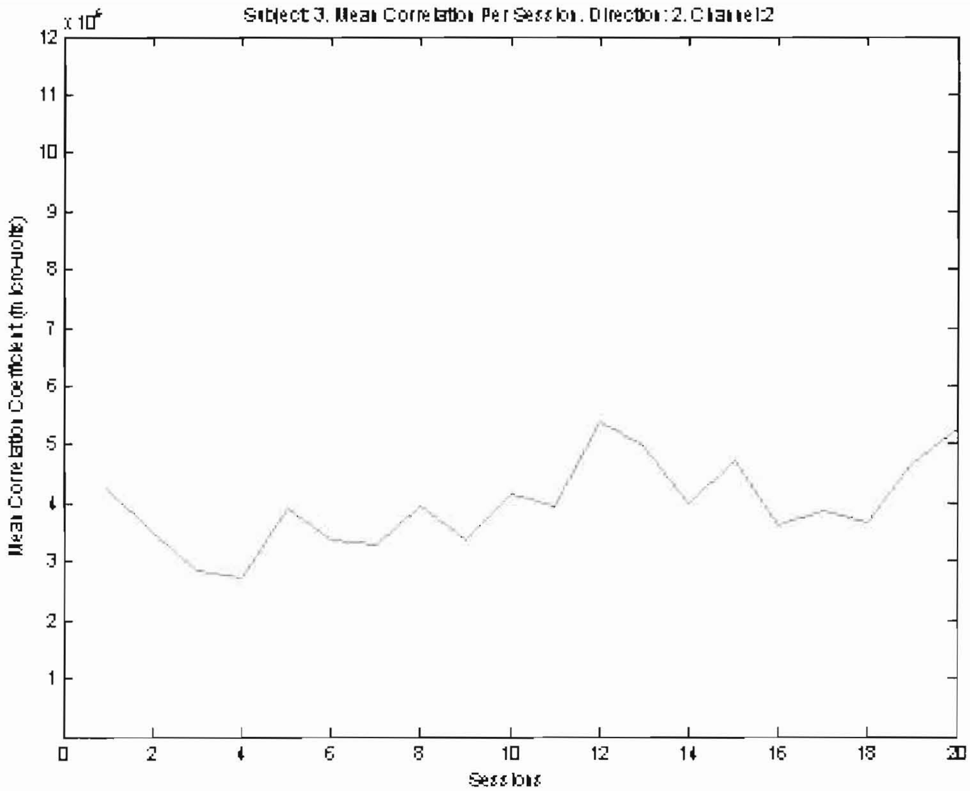

Subject: 2. Mean Correlation Per Session. Direction: 2. Channel:3
x 10^6
Mean Correlation Coefficient (micro-volts)
Sessions

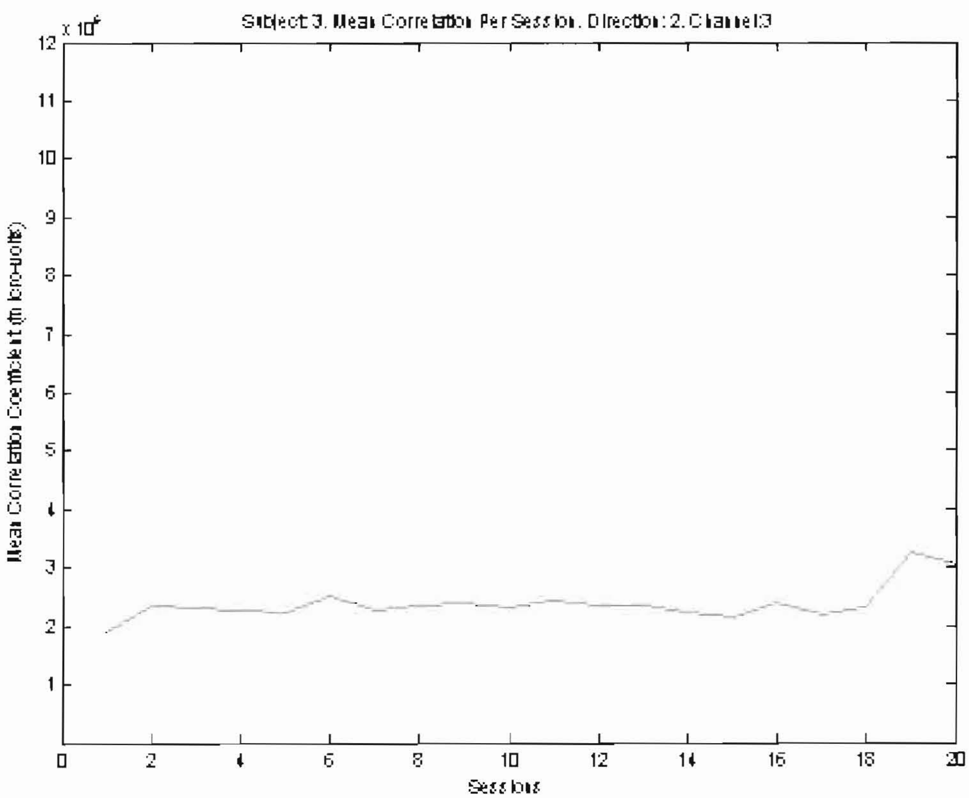

Subject 3. Mean Correlation Per Session. Direction: 1. Channel:1
Mean Correlation Coefficient (micro-volts)
Sessions
x 10^4
0
1
2
3
4
5
6
7
8
9
10
11
12
14
16
18
20

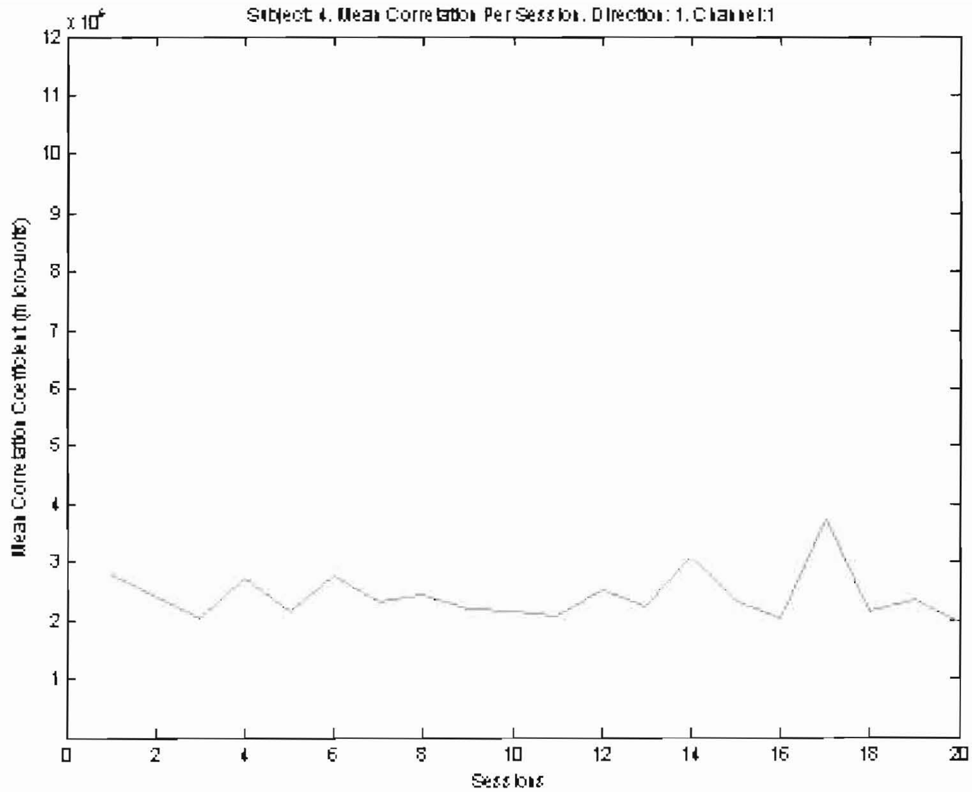

Subject 3. Mean Correlation Per Session. Direction: 1. Channel:2
Mean Correlation Coefficient (micro-volts)
Sessions
x 10^4
0
1
2
3
4
5
6
7
8
9
10
11
12
14
16
18
20


Subject 3. Mean Correlation Per Session. Direction: 1. Channel:3
x 10^4
Mean Correlation Coefficient (micro-volts)
Sessions

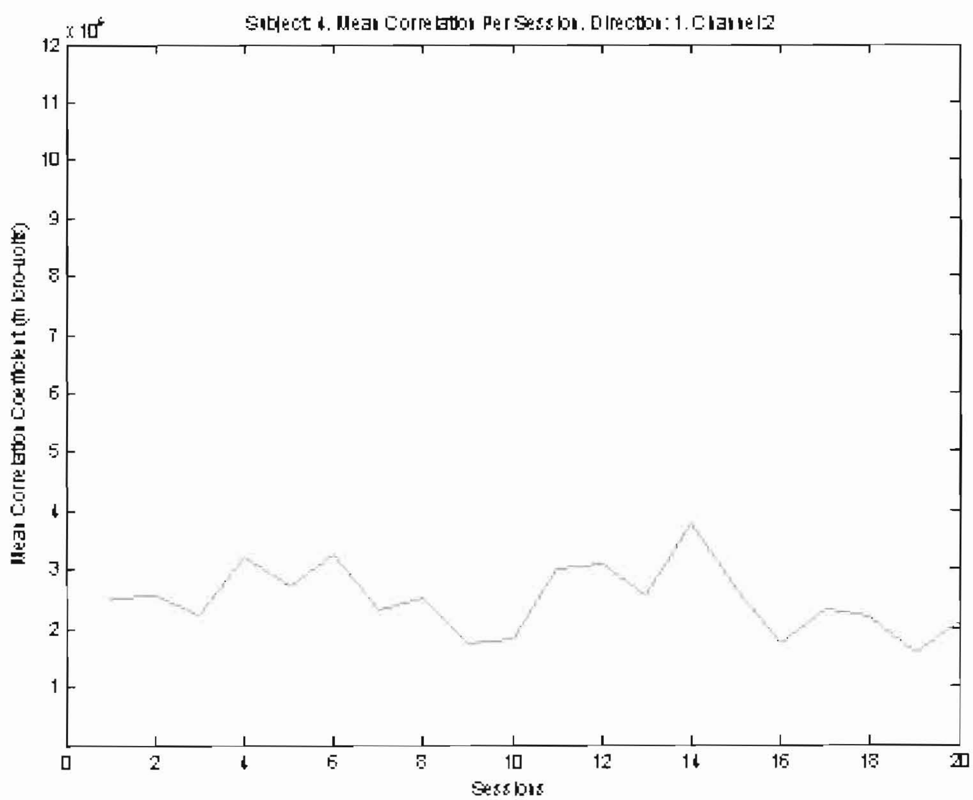

Subject 3. Mean Correlation Per Session. Direction: 2. Channel:1
x 10^4
Mean Correlation Coefficient (micro-volts)
Sessions


Subject 3. Mean Correlation Per Session. Direction: 2. Channel 2
x 10^-4
Mean Correlation Coefficient (micro-volts)
Sessions

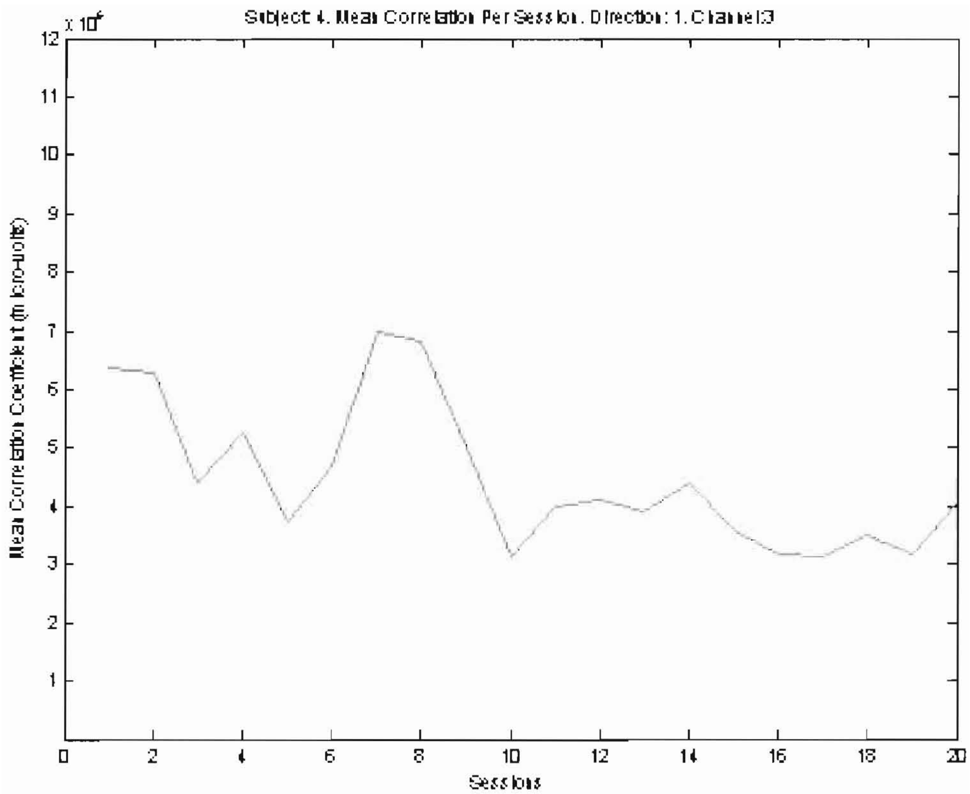

Subject 3. Mean Correlation Per Session. Direction: 2. Channel 3
x 10^-4
Mean Correlation Coefficient (micro-volts)
Sessions

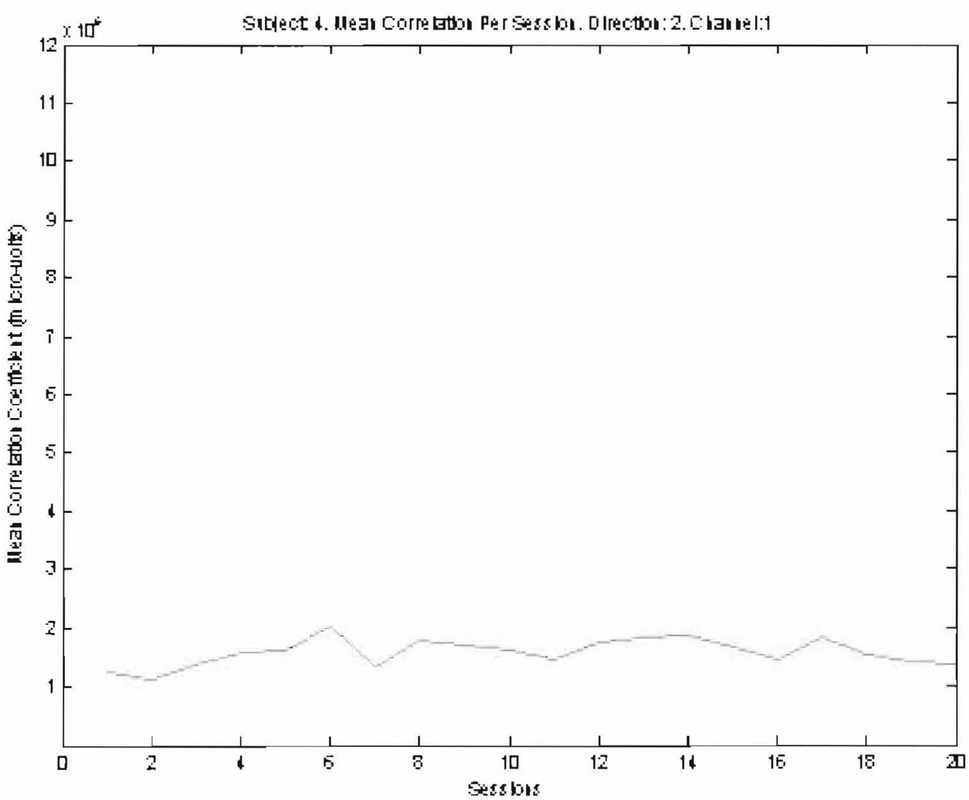


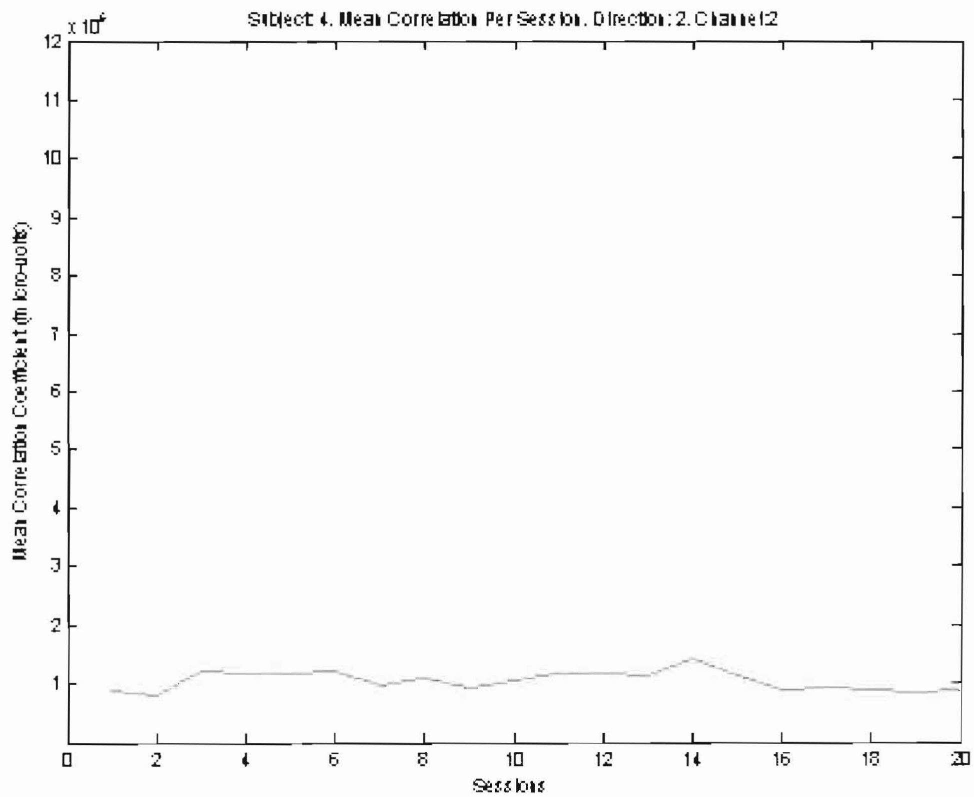
Subject 4. Mean Correlation Per Session. Direction: 1. Channel:1
Mean Correlation Coefficient (micro-volts)
Sessions

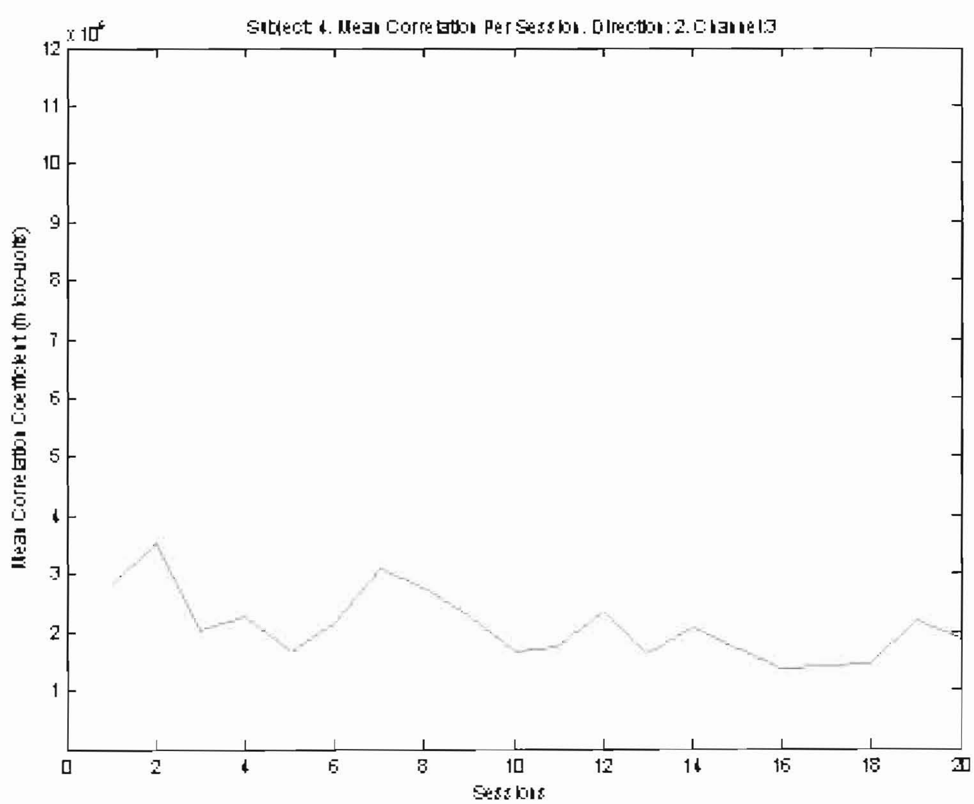


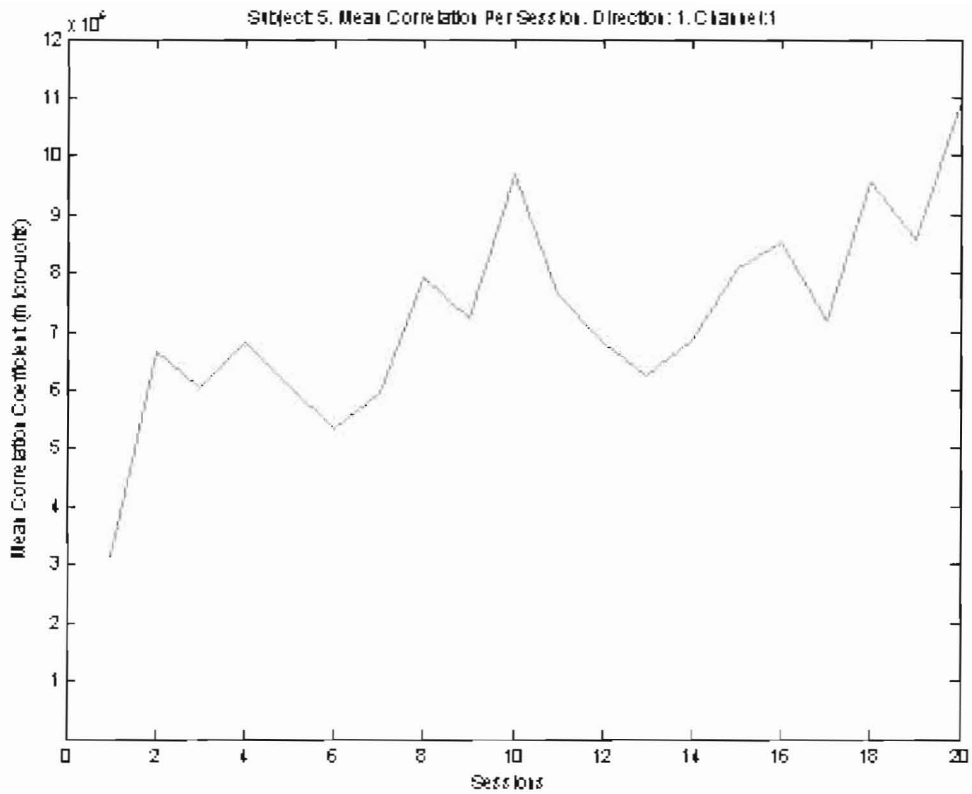
Subject 4. Mean Correlation Per Session. Direction: 1. Channel:2
Mean Correlation Coefficient (micro-volts)
Sessions

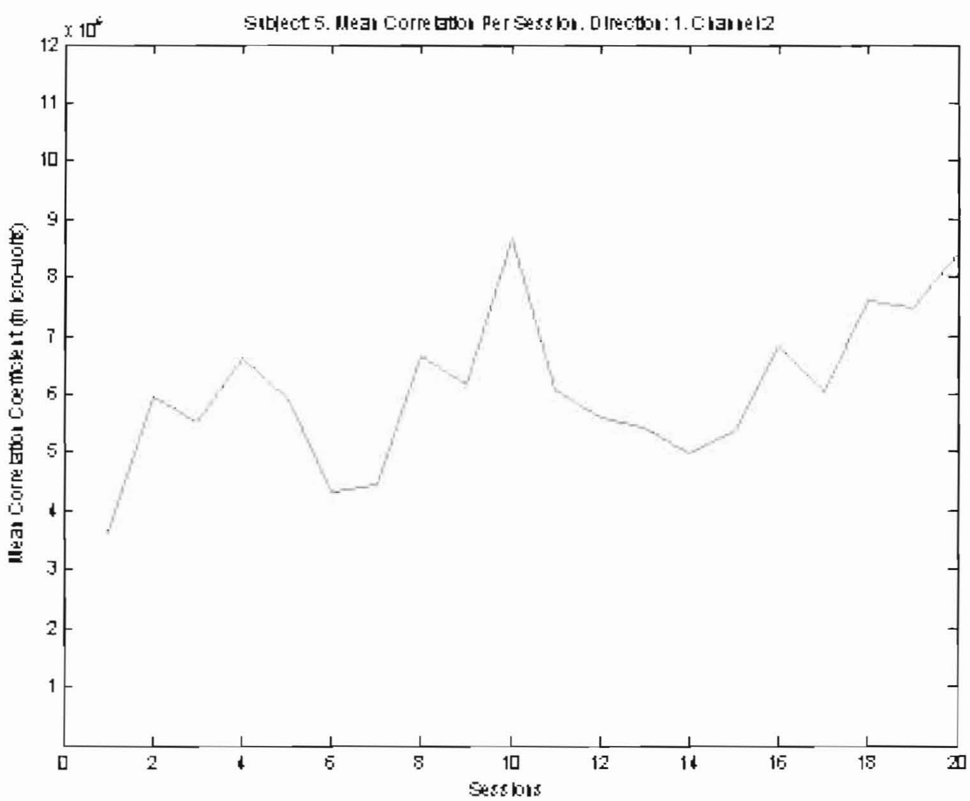

Subject: 4. Mean Correlation Per Session. Direction: 1. Channel:3
Mean Correlation Coefficient (micro-volts)
Sessions

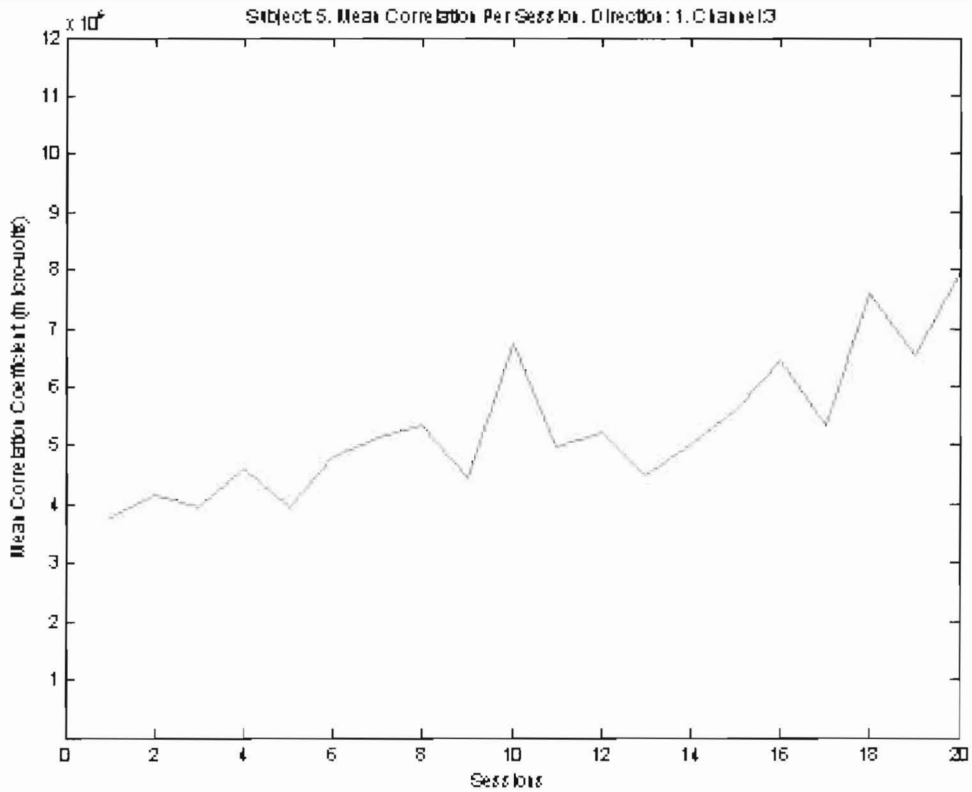

Subject: 4. Mean Correlation Per Session. Direction: 2. Channel:1
Mean Correlation Coefficient (micro-volts)
Sessions

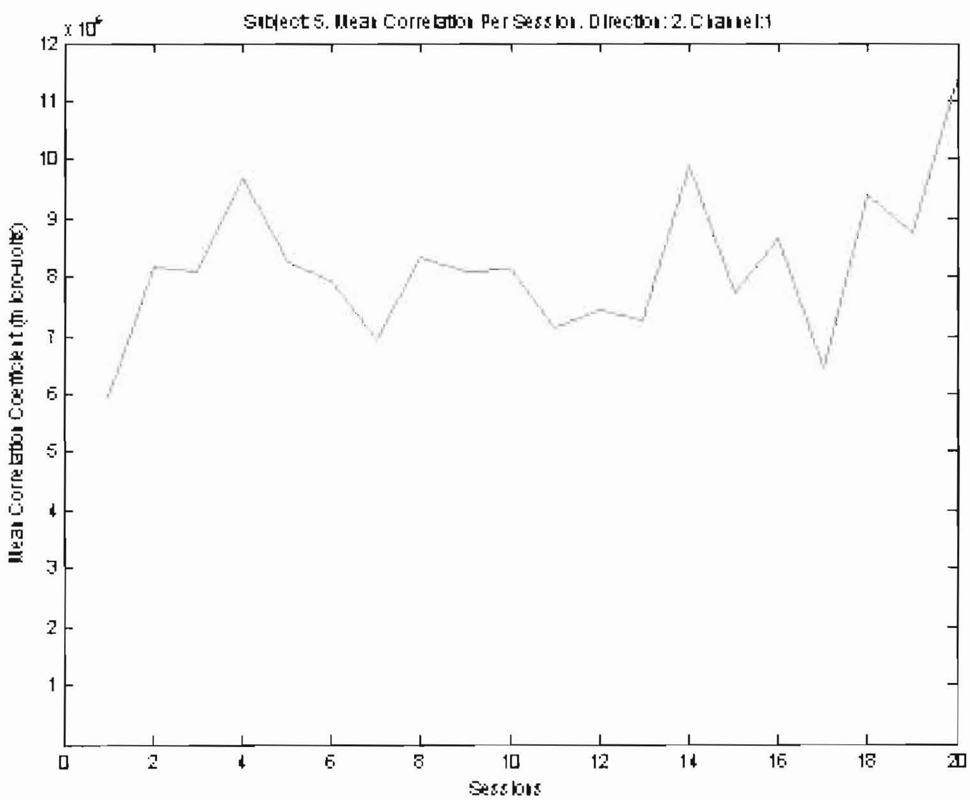

Subject: 4. Mean Correlation Per Session. Direction: 2. Channel:2
x 10^-4
Mean Correlation Coefficient (micro-volts)
Sessions
0 2 4 6 8 10 12 14 16 18 20
12 11 10 9 8 7 6 5 4 3 2 1

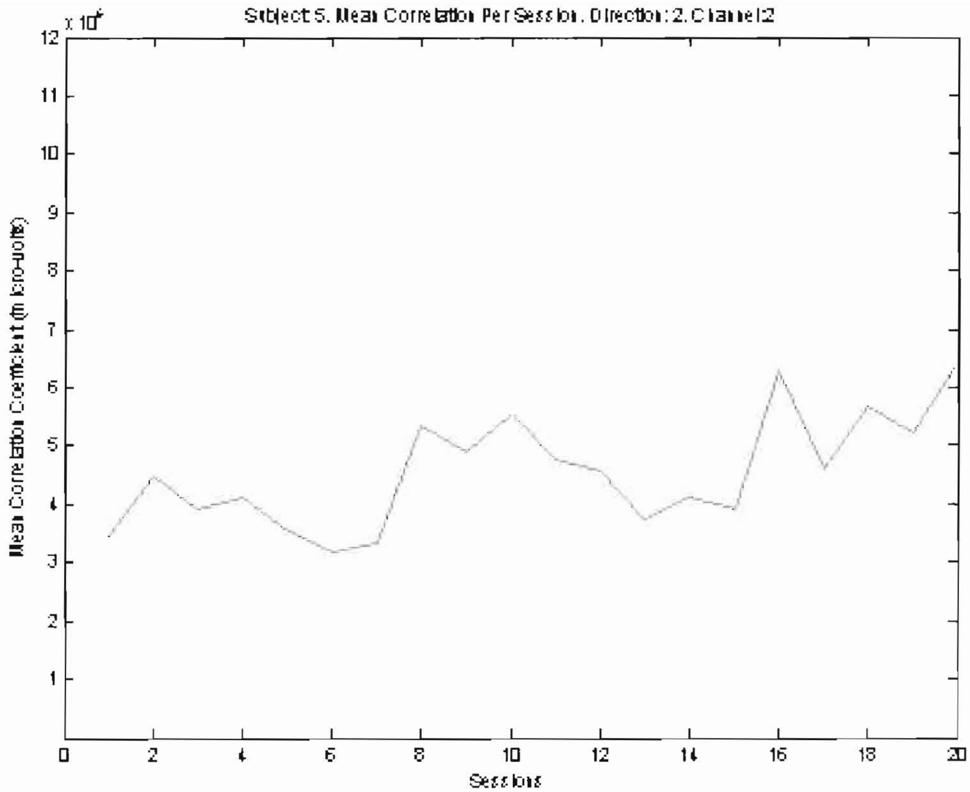

Subject: 4. Mean Correlation Per Session. Direction: 2. Channel:3
x 10^-4
Mean Correlation Coefficient (micro-volts)
Sessions
0 2 4 6 8 10 12 14 16 18 20
12 11 10 9 8 7 6 5 4 3 2 1

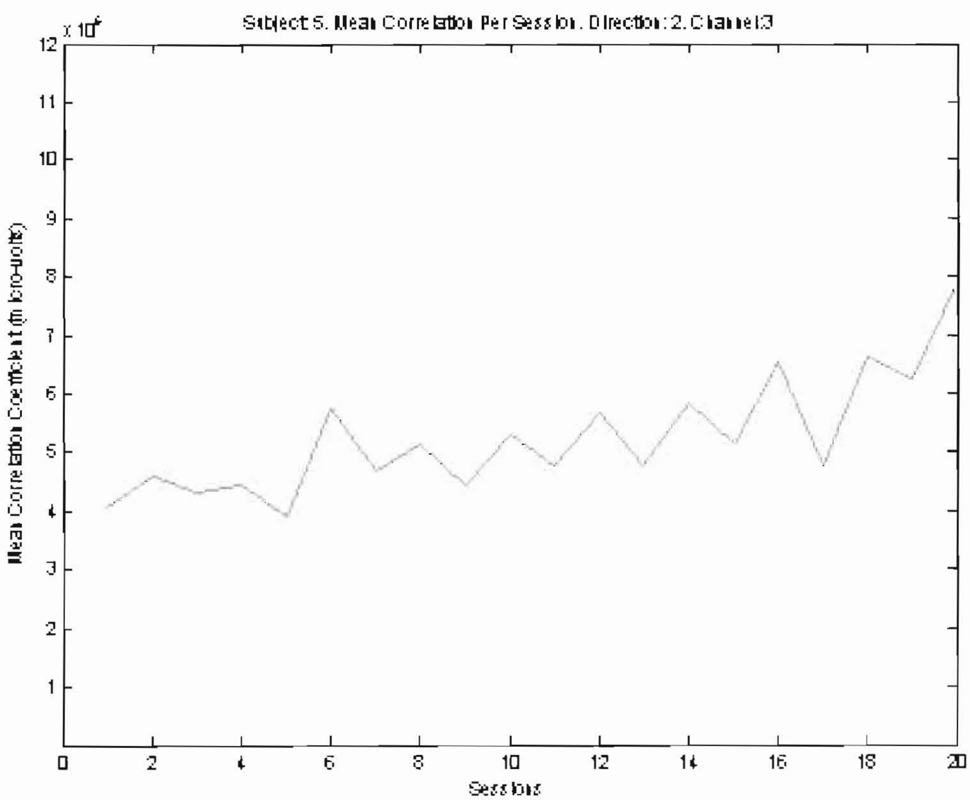

Subject 5. Mean Correlation Per Session. Direction: 1. Channel:1
Mean Correlation Coefficient (micro-volts)
Sessions


Subject 5. Mean Correlation Per Session. Direction: 1. Channel:2
Mean Correlation Coefficient (micro-volts)
Sessions

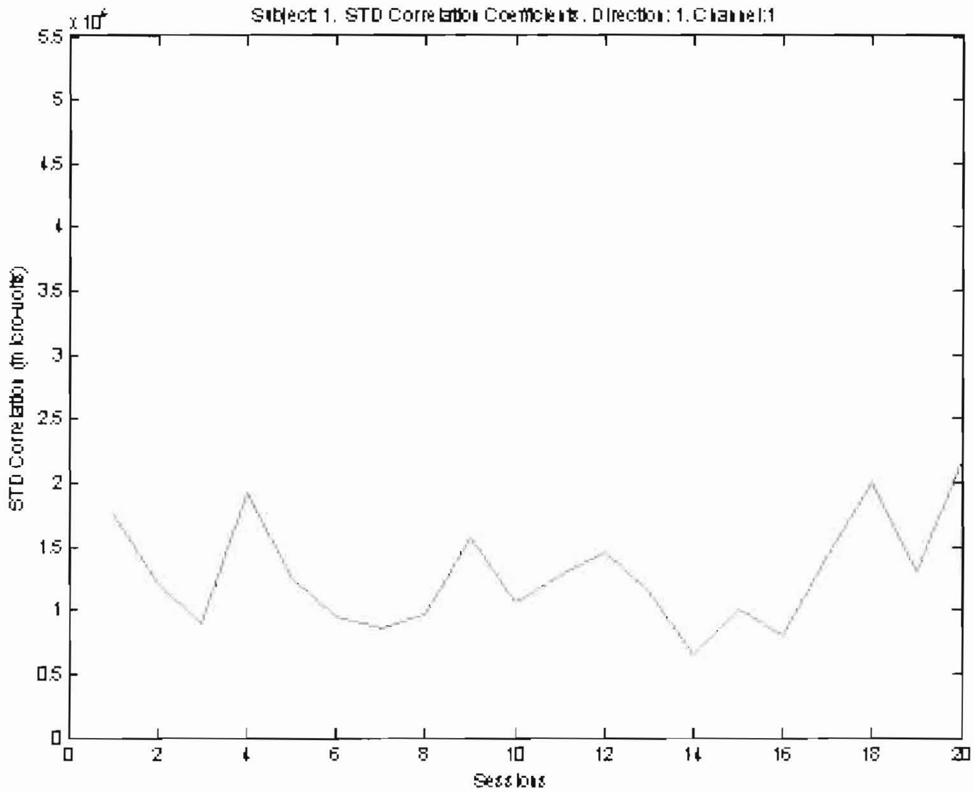

Subject 5. Mean Correlation Per Session. Direction: 1. Channel:3
x 10⁻⁶
Mean Correlation Coefficient (micro-volts)
Sessions

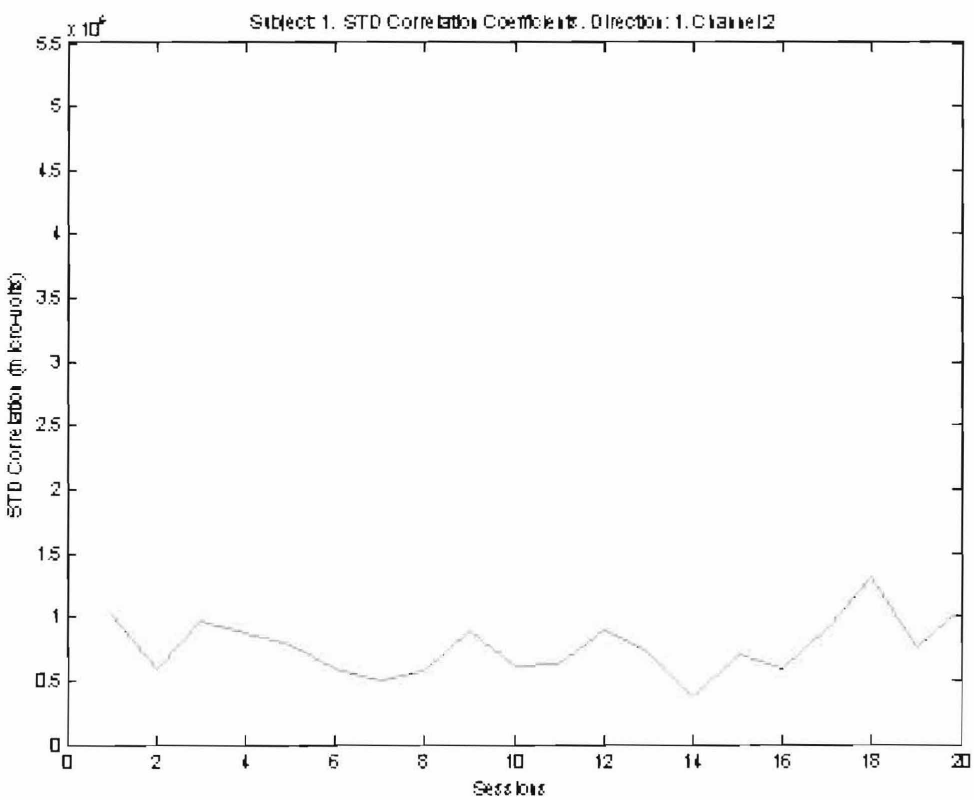

Subject 5. Mean Correlation Per Session. Direction: 2. Channel:1
x 10⁻⁶
Mean Correlation Coefficient (micro-volts)
Sessions

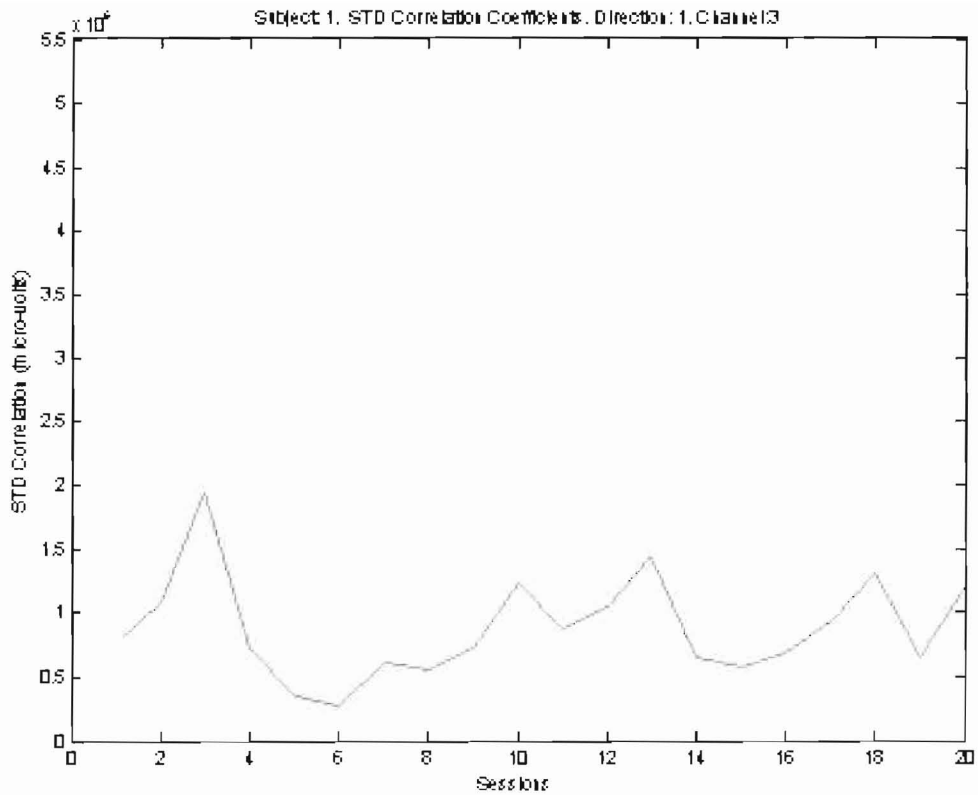

Subject 5. Mean Correlation Per Session. Direction: 2. Channel 2
Mean Correlation Coefficient (micro-volts)
Sessions

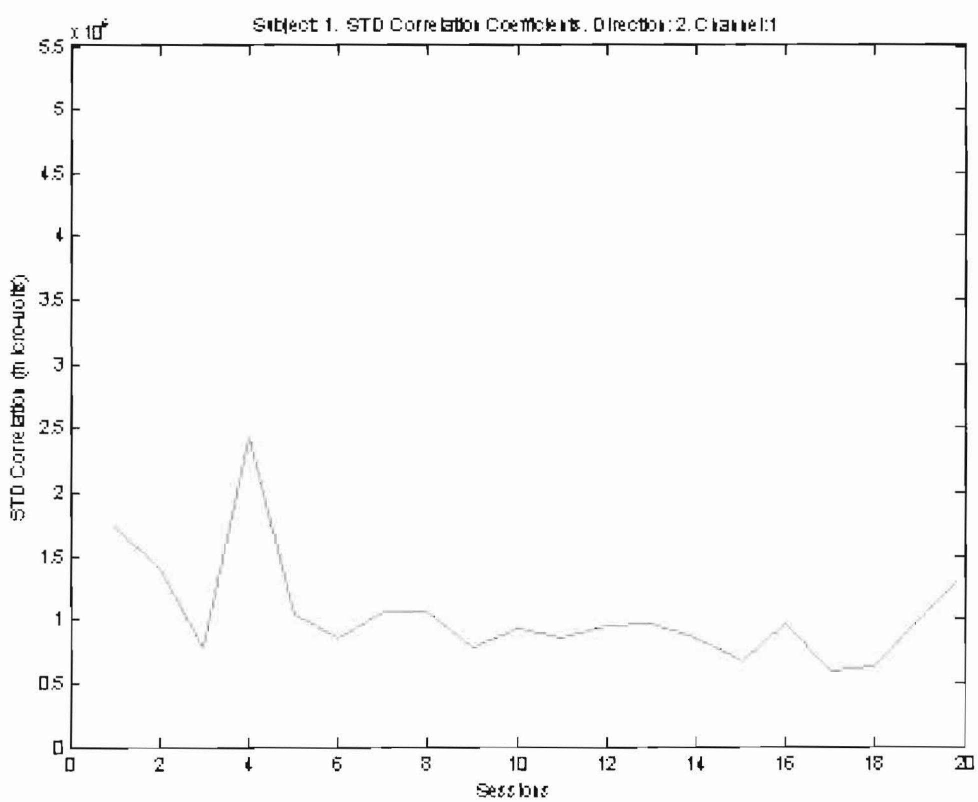

Subject 5. Mean Correlation Per Session. Direction: 2. Channel 3
Mean Correlation Coefficient (micro-volts)
Sessions

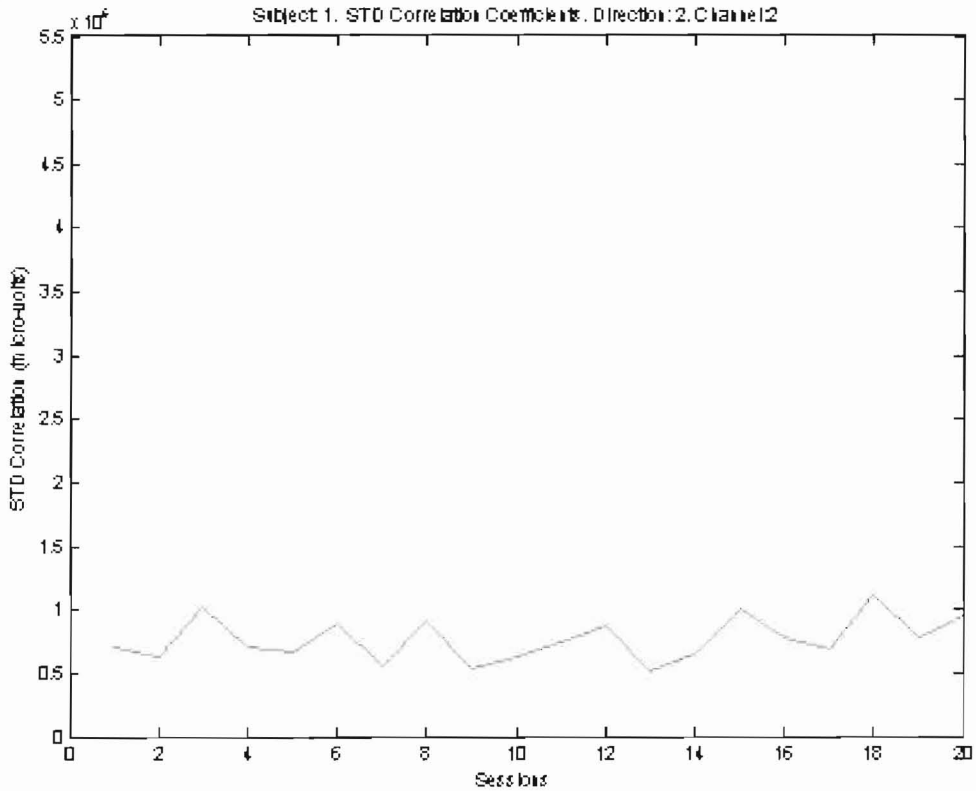
APPENDIX 7: MEAN STANDARD DEVIATION OF CORRELATION COEFFICIENTS PER SESSION RESULTS

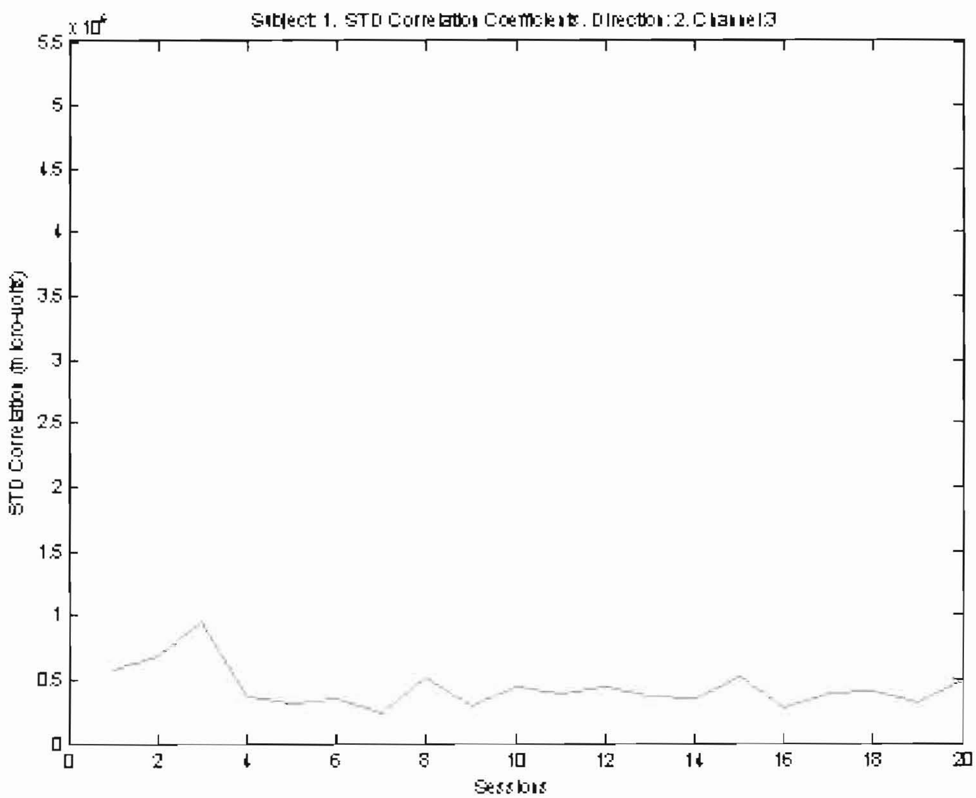

Subject 1. STD Correlation Coefficients. Direction: 1. Channel:1
STD Correlation (micro-volts)
Sessions

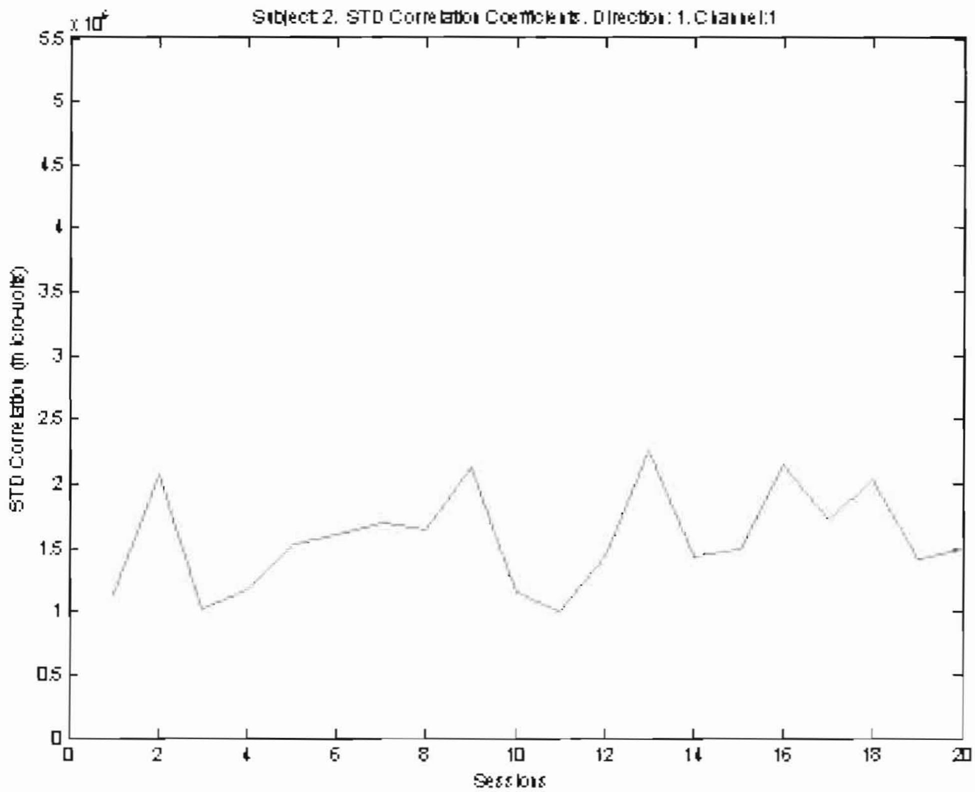

Subject 1. STD Correlation Coefficients. Direction: 1. Channel:2
STD Correlation (micro-volts)
Sessions

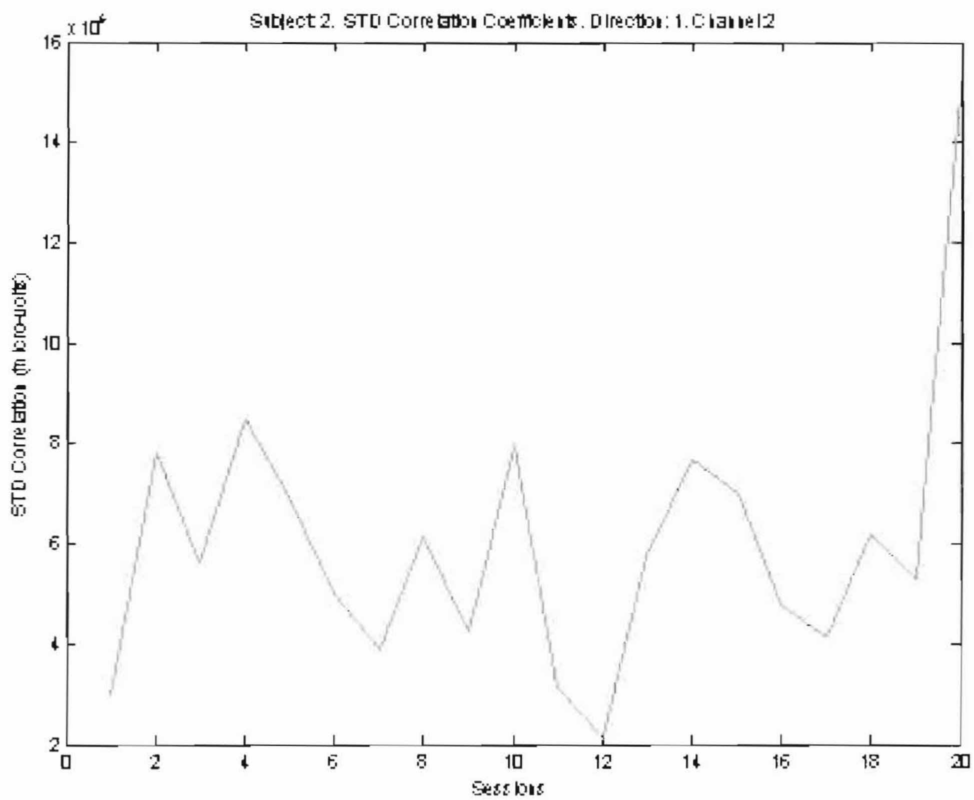

Subject: 1. STD Correlation Coefficients. Direction: 1. Channel:3
STD Correlation (micro-volts)
Sessions

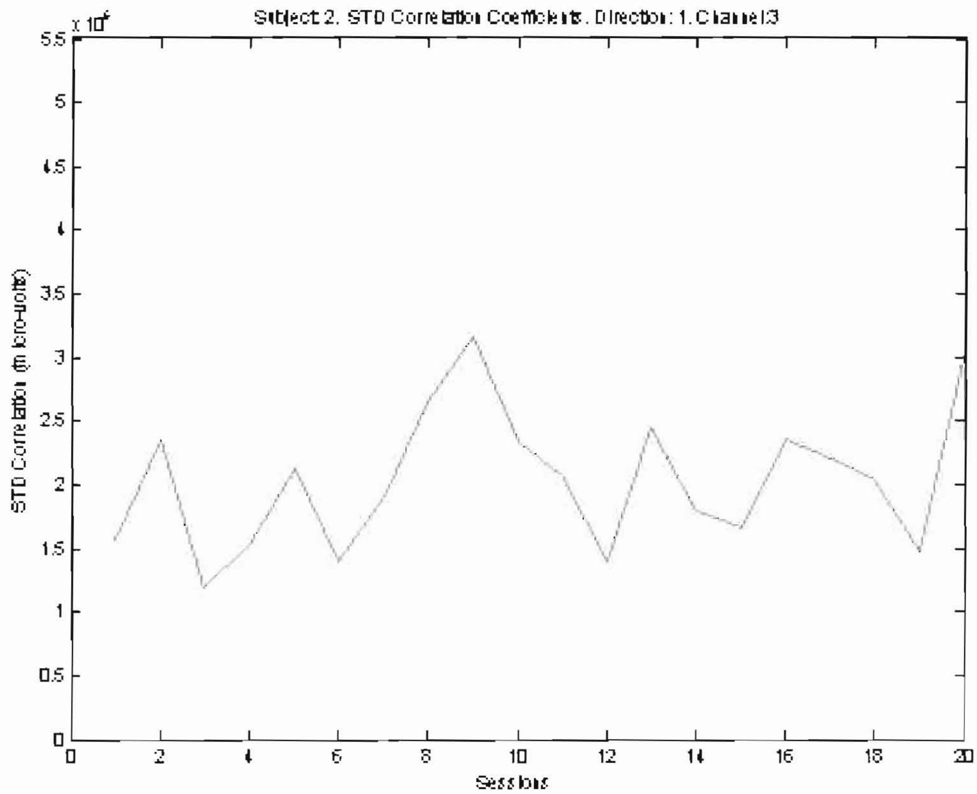

Subject: 1. STD Correlation Coefficients. Direction: 2. Channel:1
STD Correlation (micro-volts)
Sessions

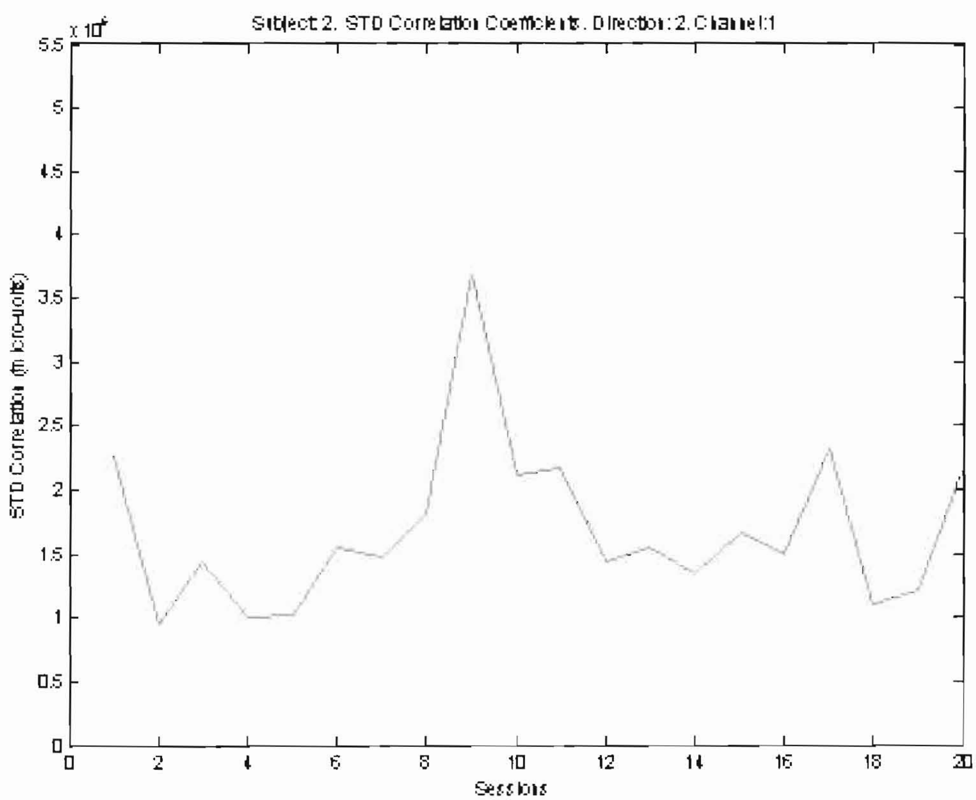

Subject 1. STD Correlation Coefficients. Direction: 2. Channel 2
STD Correlation (micro-volts)
Sessions

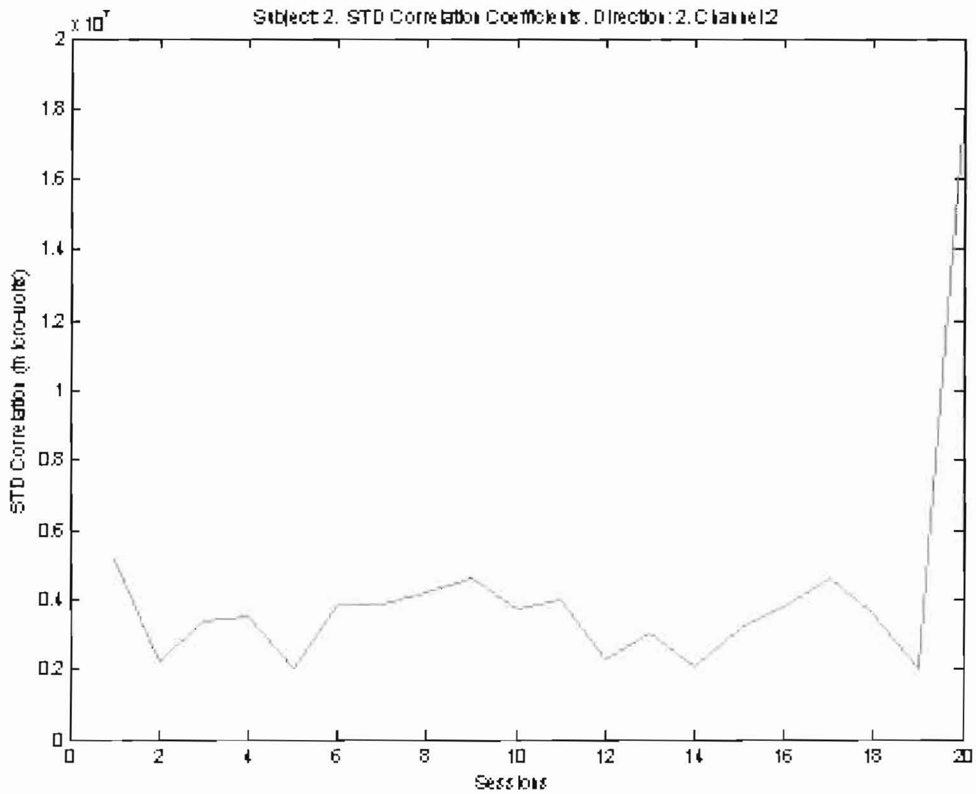

Subject 1. STD Correlation Coefficients. Direction: 2. Channel 3
STD Correlation (micro-volts)
Sessions

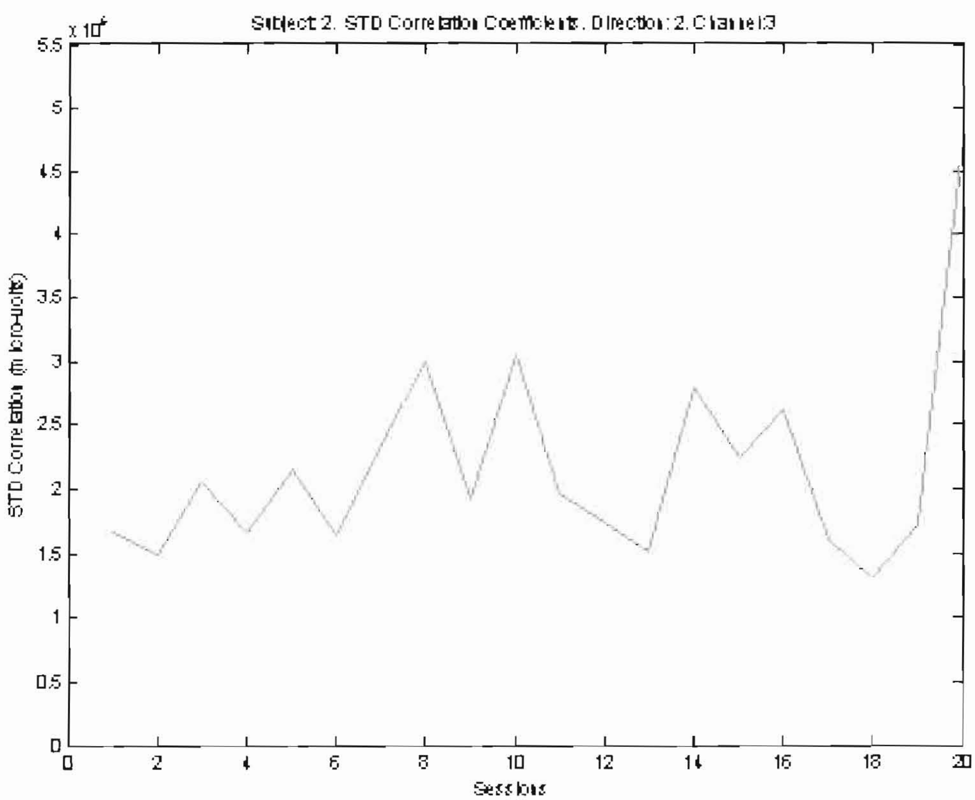

Subject: 2. STD Correlation Coefficients. Direction: 1. Channel:1
x 10
STD Correlation (micro-volts)
Sessions

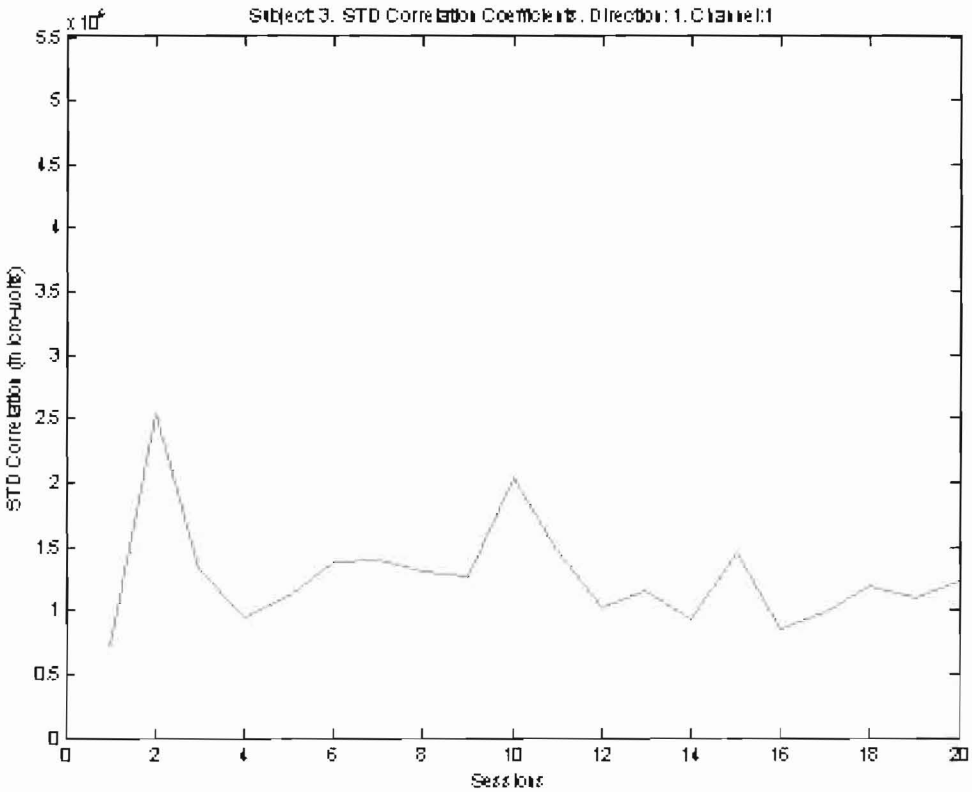

Subject: 2. STD Correlation Coefficients. Direction: 1. Channel:2
x 10
STD Correlation (micro-volts)
Sessions

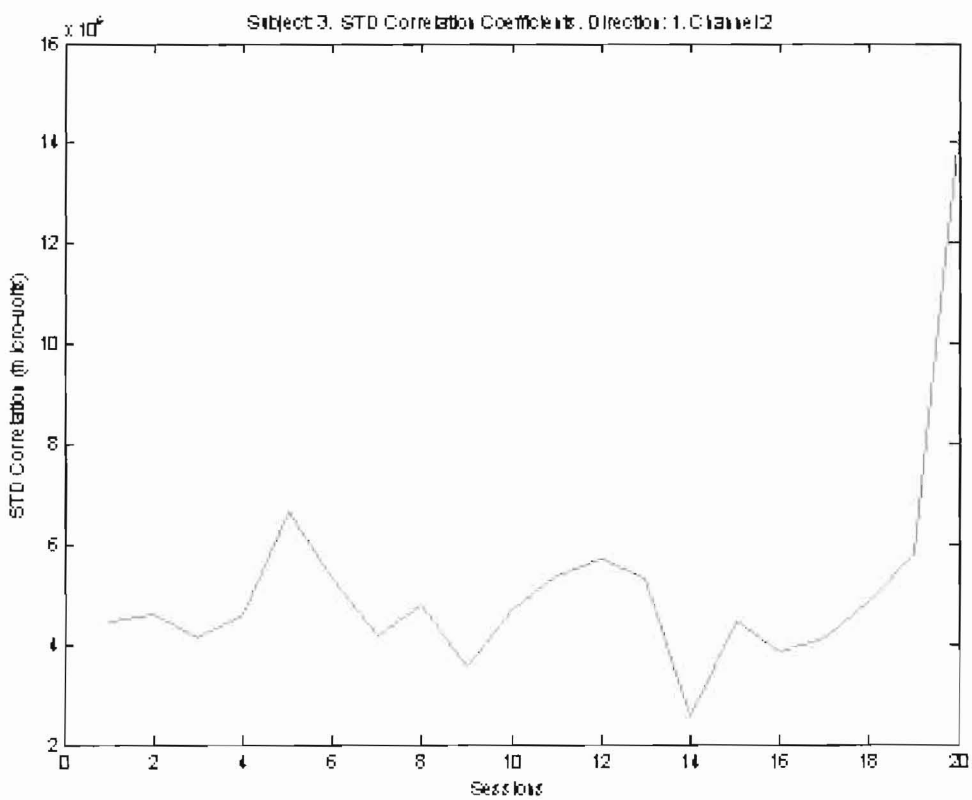

Subject 2. STD Correlation Coefficients. Direction: 1. Channel:3
STD Correlation (micro-volts)
Sessions

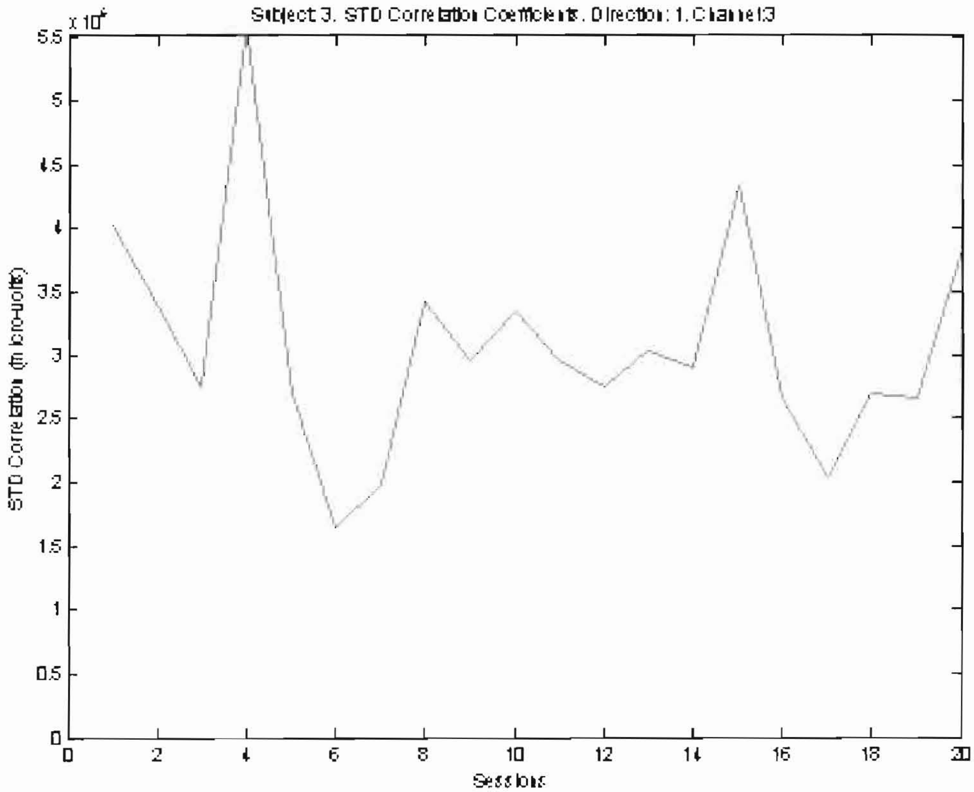

Subject 2. STD Correlation Coefficients. Direction: 2. Channel:1
STD Correlation (micro-volts)
Sessions

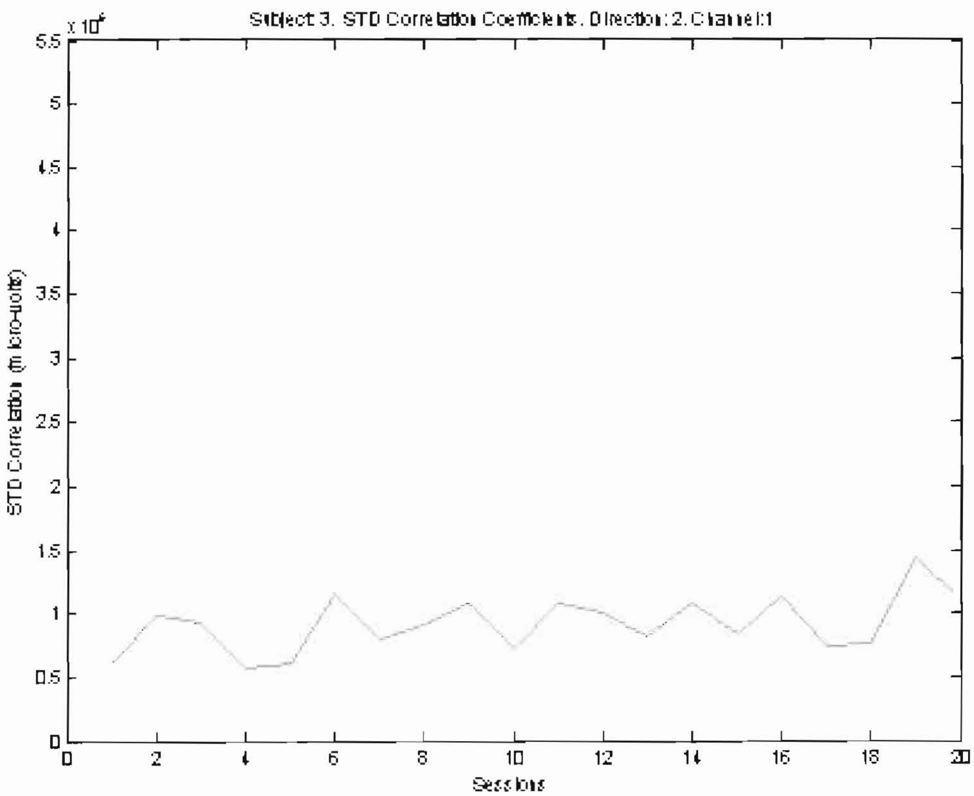

Subject: 2. STD Correlation Coefficients. Direction: 2. Channel:2
x 10^7
STD Correlation (micro-volts)
Sessions

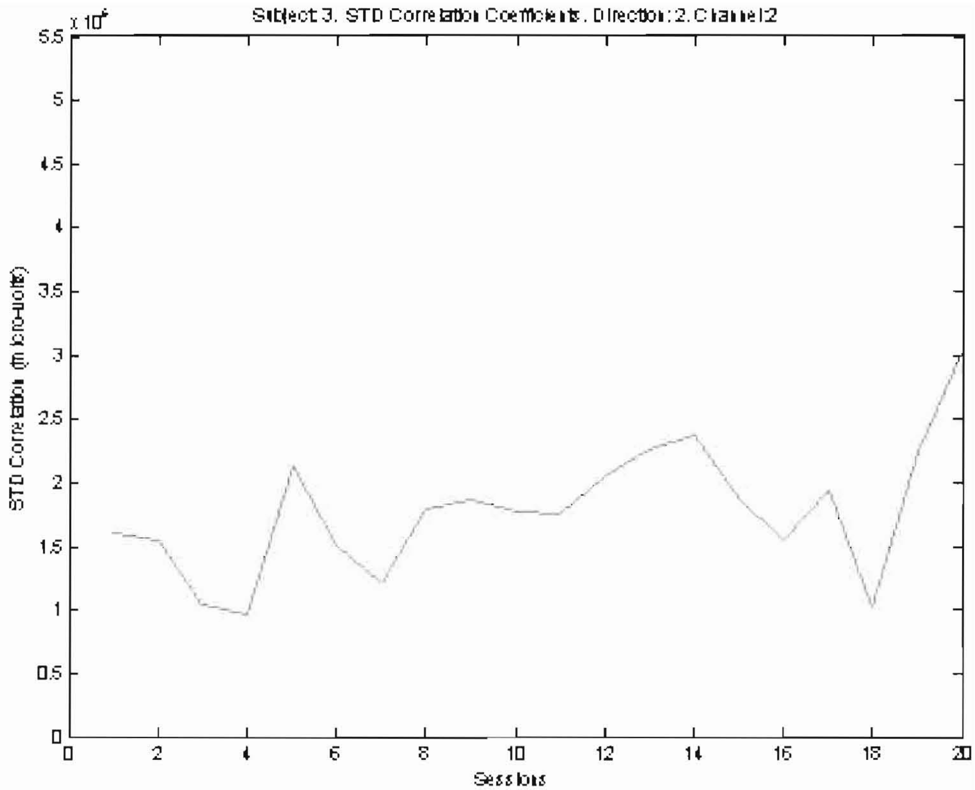

Subject: 2. STD Correlation Coefficients. Direction: 2. Channel:3
x 10^6
STD Correlation (micro-volts)
Sessions


Subject 3. STD Correlation Coefficients. Direction: 1. Channel:1
x 10^4
STD Correlation (micro-volts)
Sessions

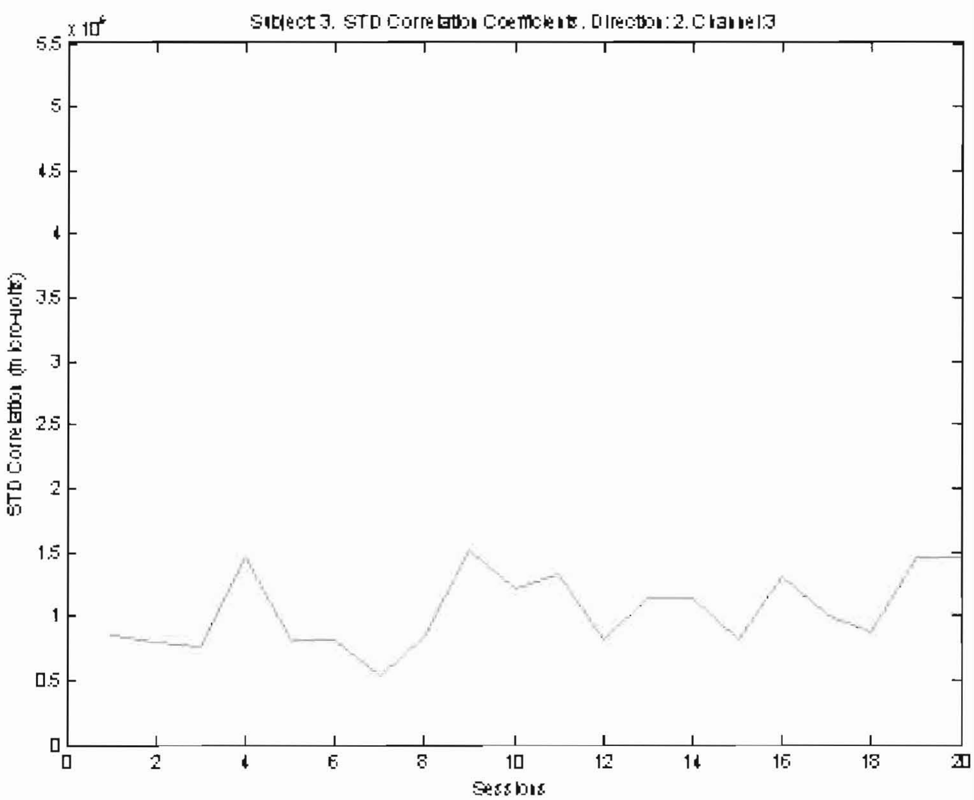

Subject 3. STD Correlation Coefficients. Direction: 1. Channel:2
x 10^4
STD Correlation (micro-volts)
Sessions


Subject 3. STD Correlation Coefficients. Direction: 1. Channel:3
STD Correlation (micro-volts)
Sessions

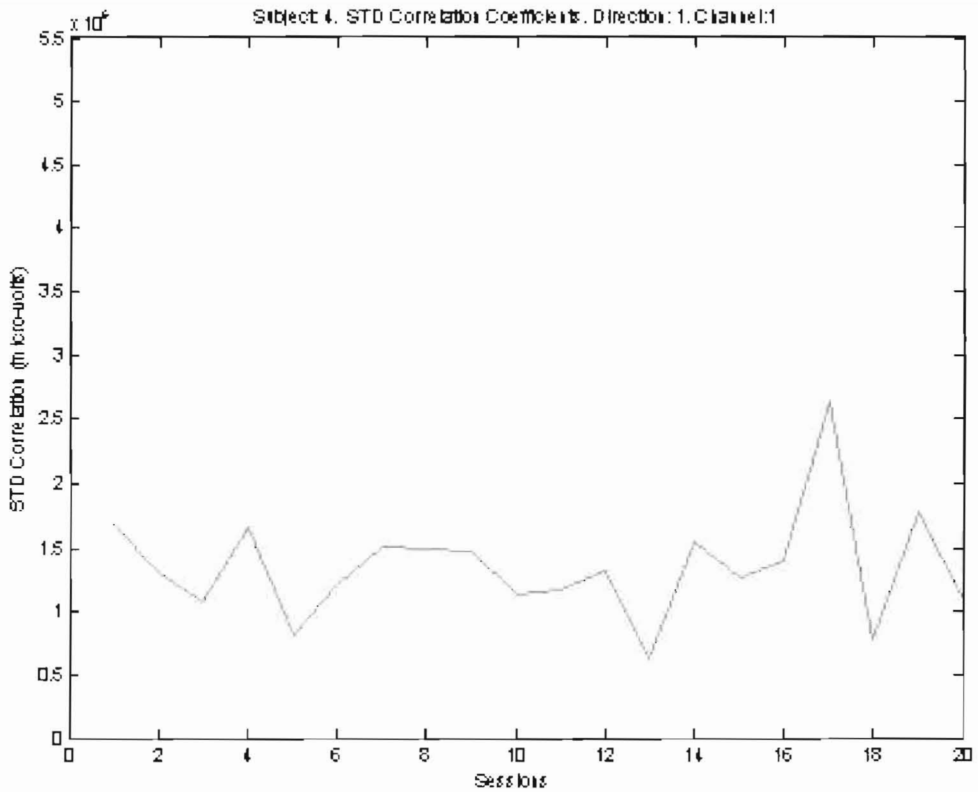

Subject 3. STD Correlation Coefficients. Direction: 2. Channel:1
STD Correlation (micro-volts)
Sessions

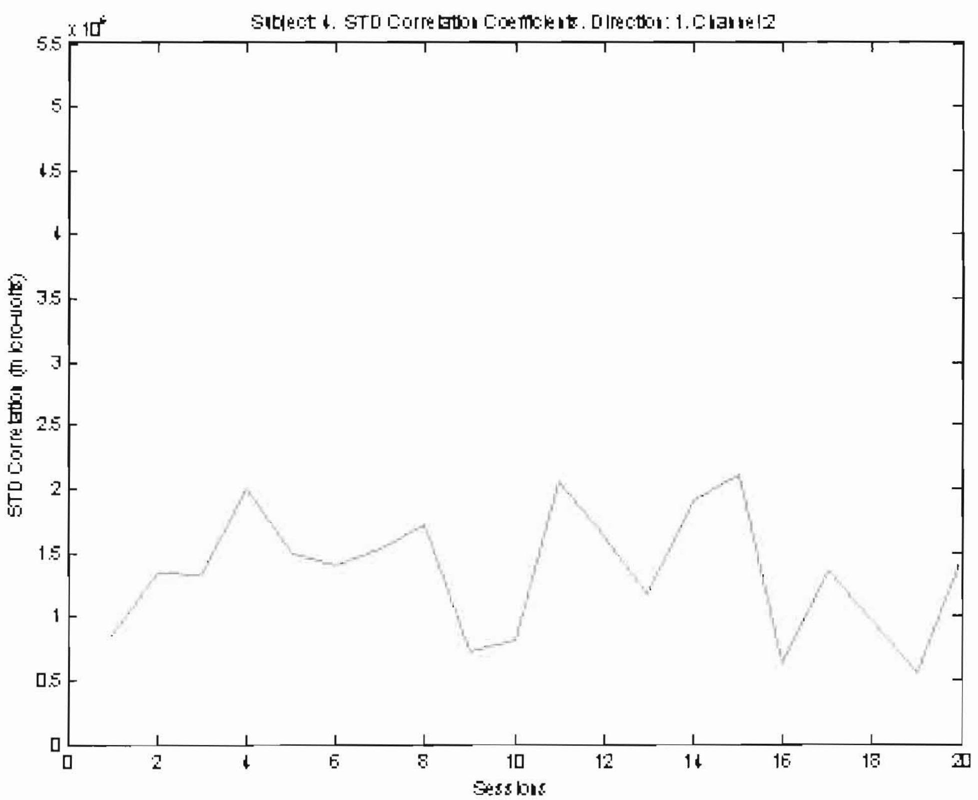


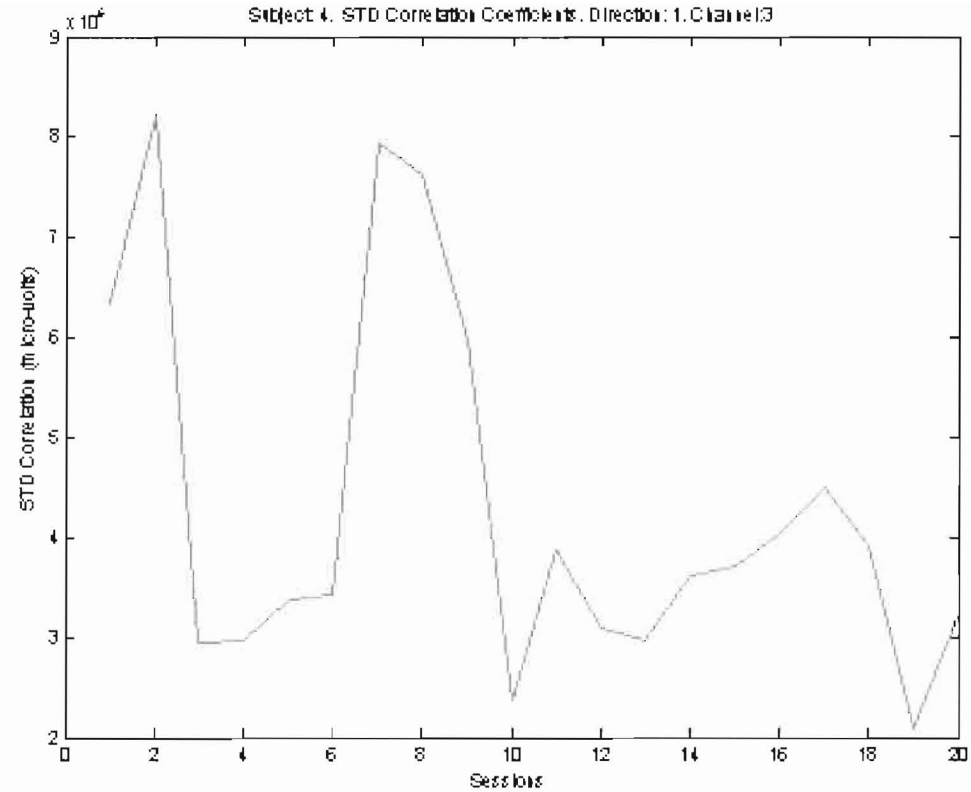
Subject 3. STD Correlation Coefficients. Direction: 2. Channel 2
STD Correlation (micro-volts)
Sessions

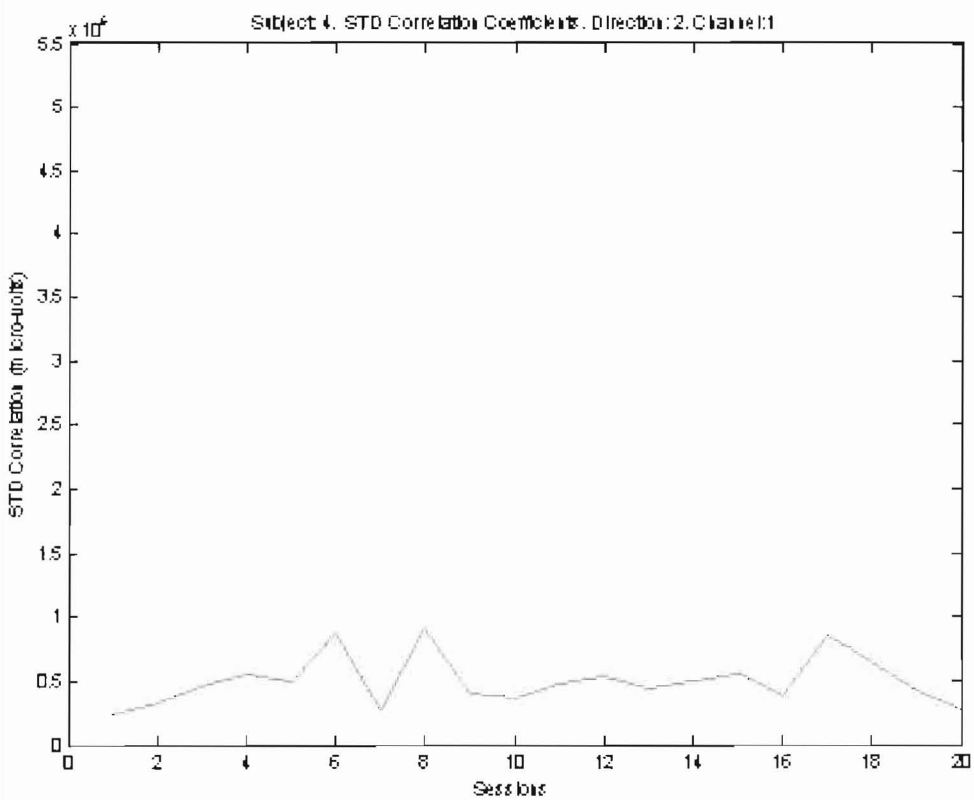


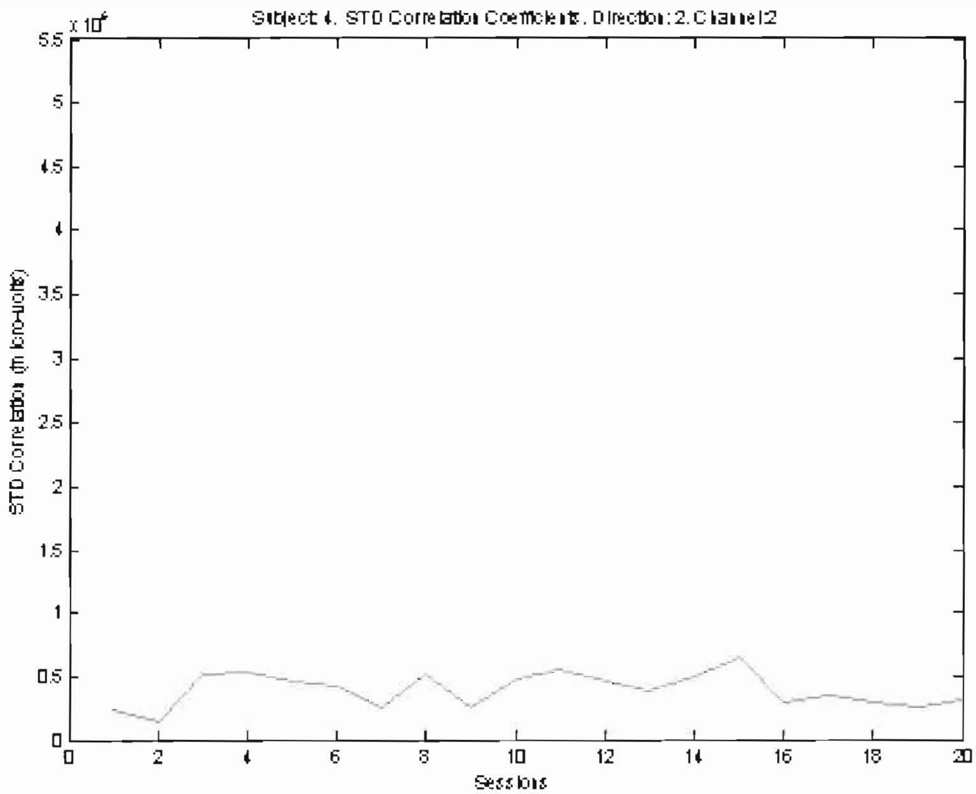
Subject 3. STD Correlation Coefficients. Direction: 2. Channel 3
STD Correlation (micro-volts)
Sessions

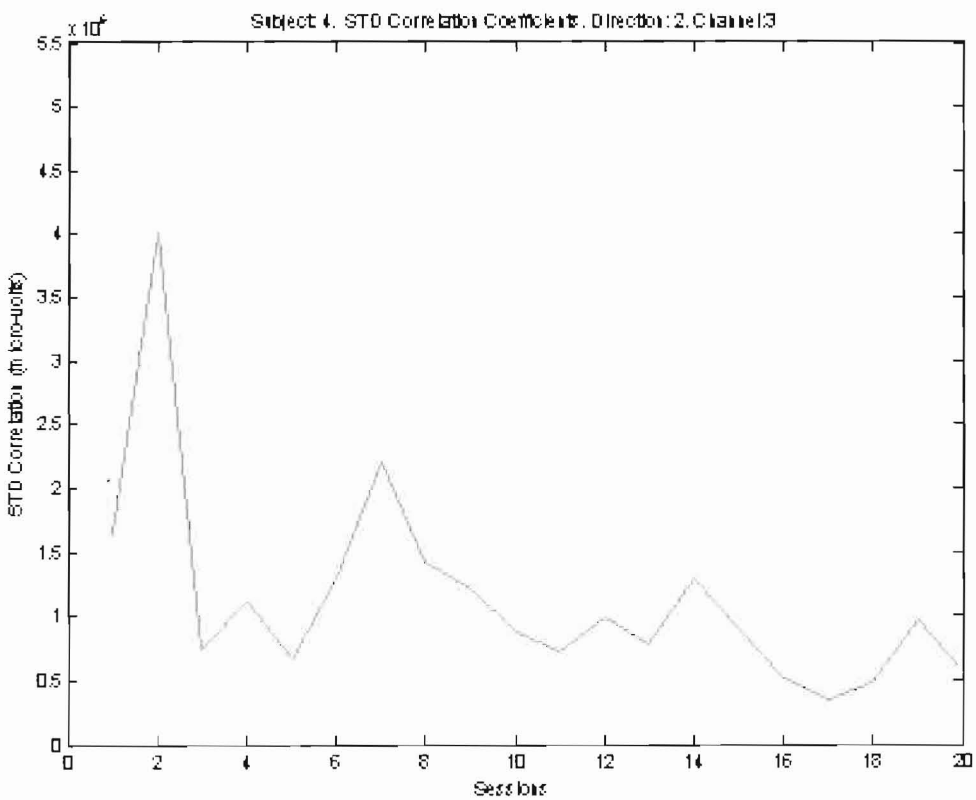

Subject: 4. STD Correlation Coefficients. Direction: 1. Channel:1
STD Correlation (micro-volts)
Sessions

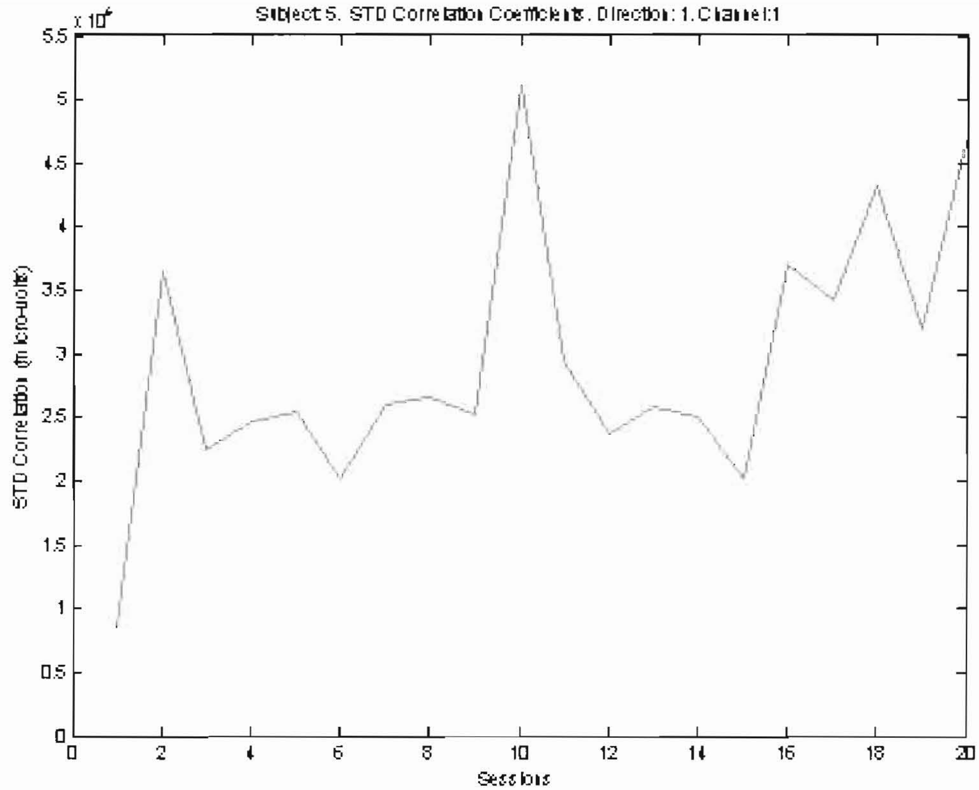

Subject: 4. STD Correlation Coefficients. Direction: 1. Channel:2
STD Correlation (micro-volts)
Sessions

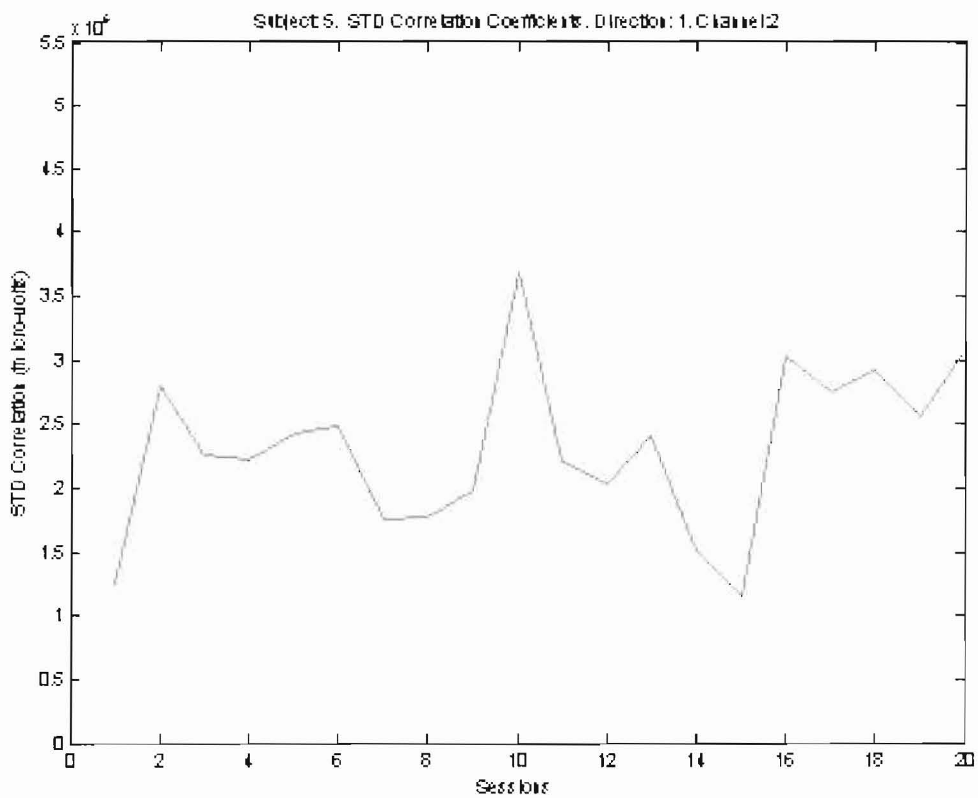

Subject 4. STD Correlation Coefficients. Direction: 1. Channel:3
STD Correlation (micro-volts)
Sessions

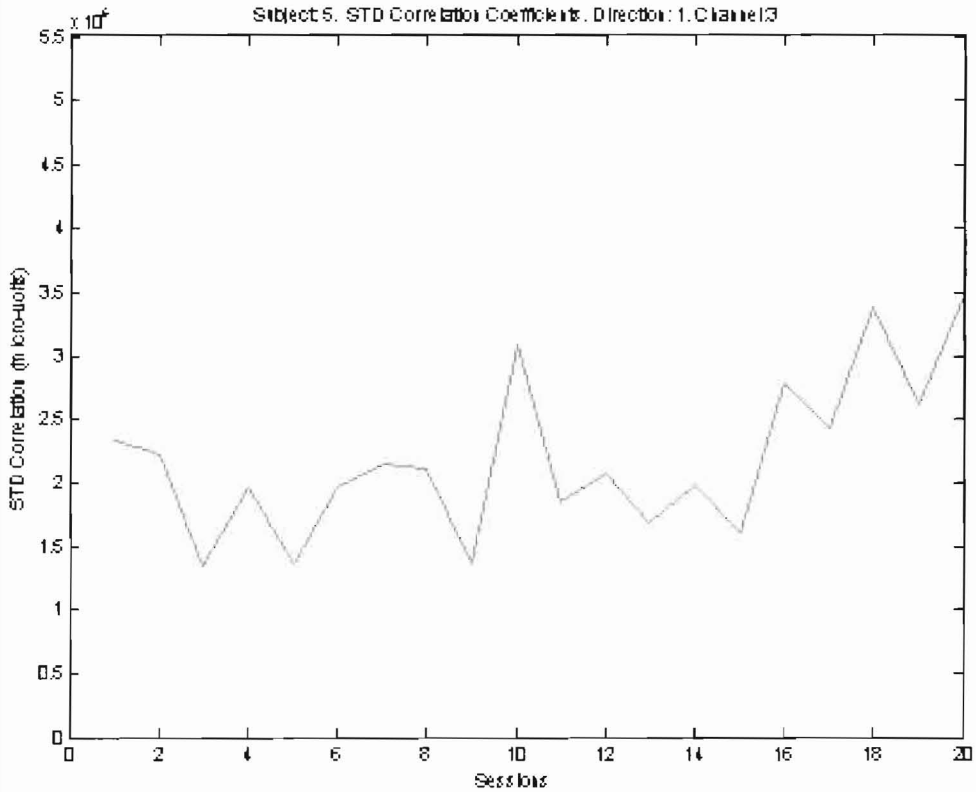

Subject 4. STD Correlation Coefficients. Direction: 2. Channel:1
STD Correlation (micro-volts)
Sessions

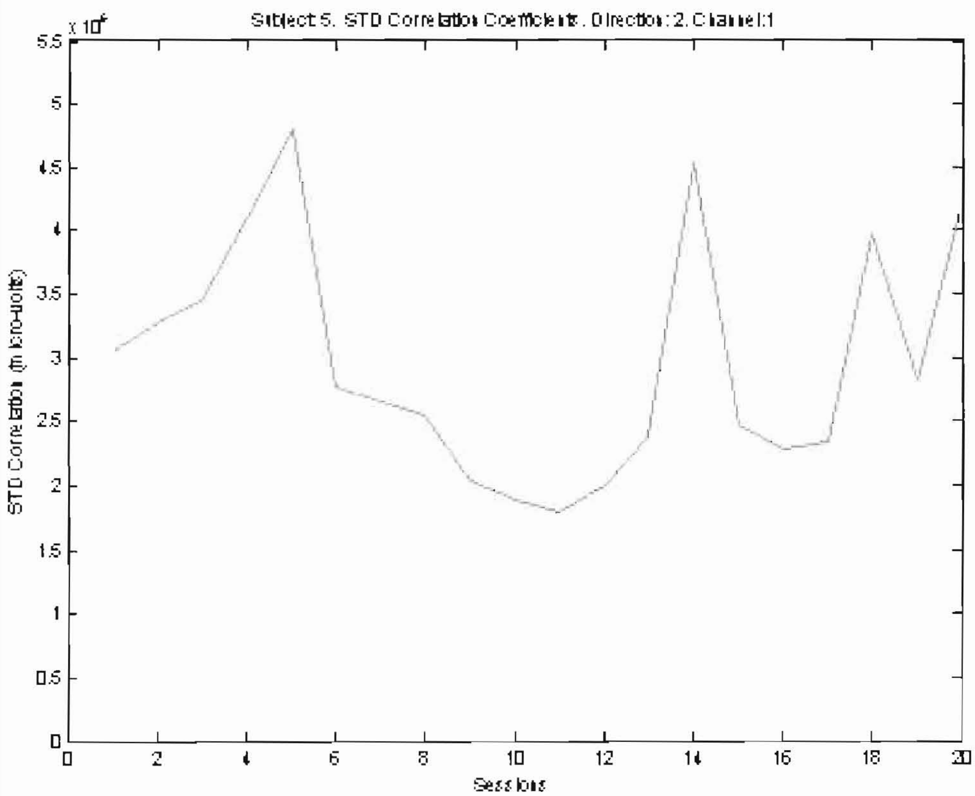

Subject 4. STD Correlation Coefficients. Direction: 2. Channel 2
x 10^-6
STD Correlation (micro-volts)
Sessions

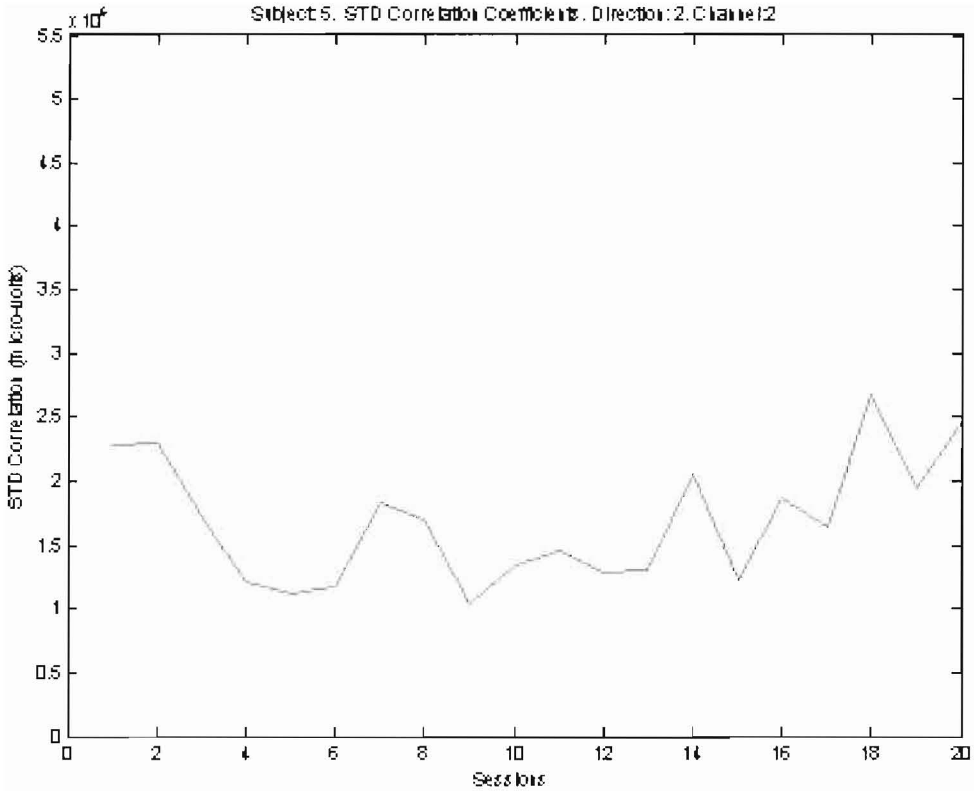

Subject 4. STD Correlation Coefficients. Direction: 2. Channel 3
x 10^-6
STD Correlation (micro-volts)
Sessions

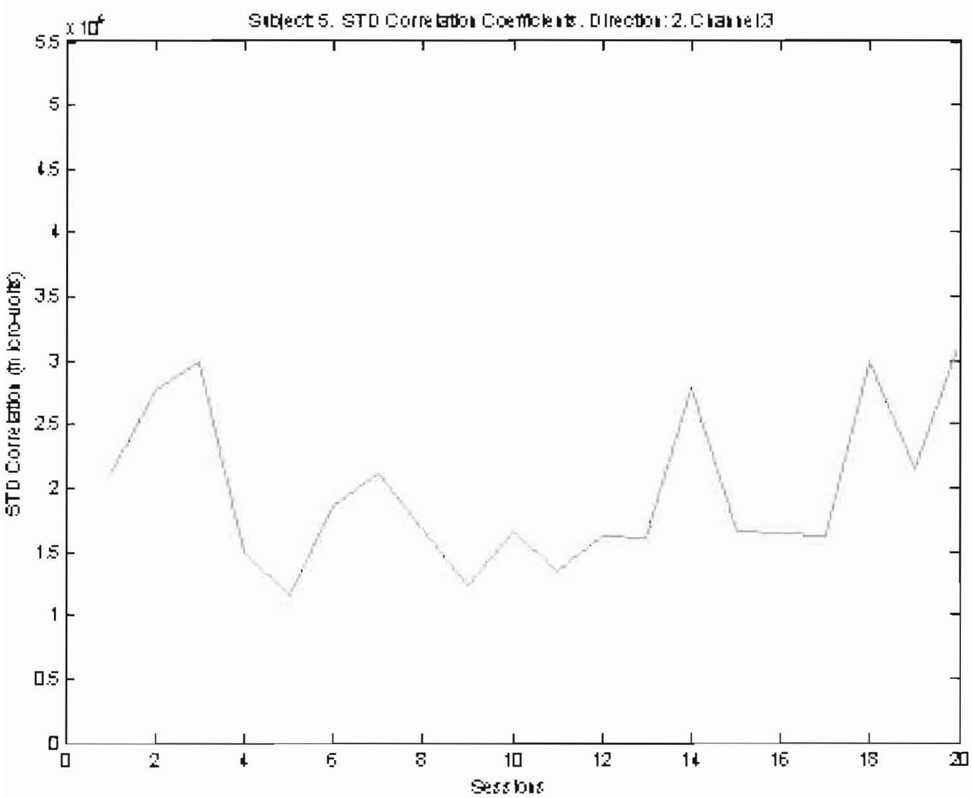

Subject 5. STD Correlation Coefficients. Direction: 1. Channel:1
x 10^-6
STD Correlation (micro-volts)
Sessions


Subject 5. STD Correlation Coefficients. Direction: 1. Channel:2
x 10^-6
STD Correlation (micro-volts)
Sessions


Subject 5. STD Correlation Coefficients. Direction: 1. Channel 3
STD Correlation (micro-volts)
Sessions

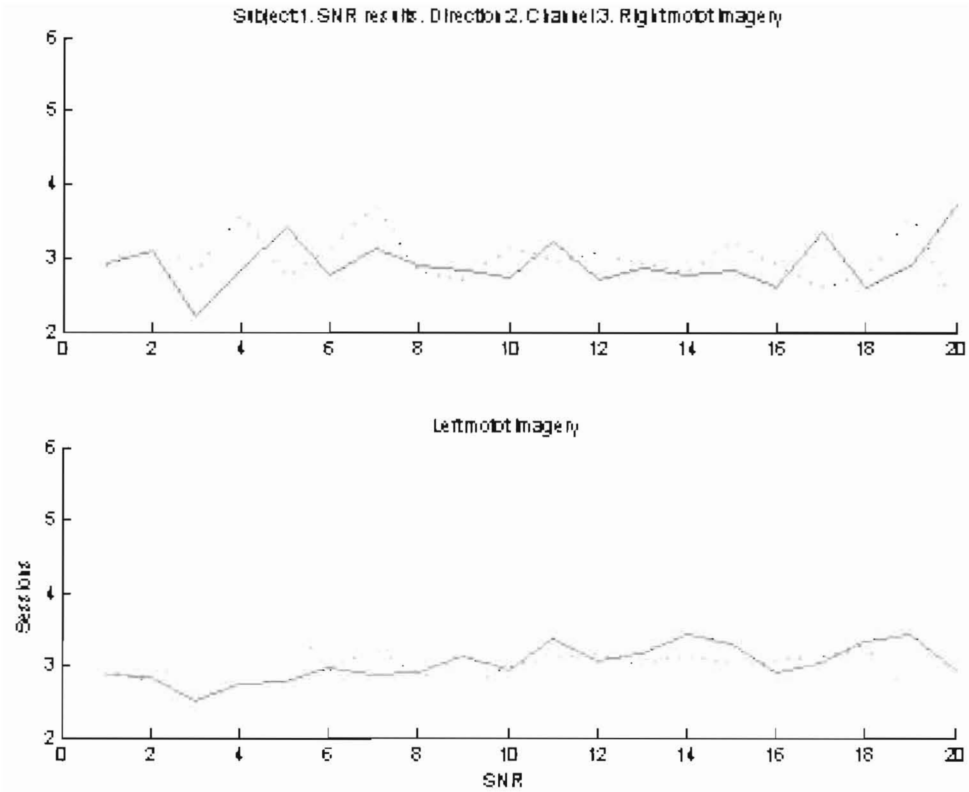

Subject 5. STD Correlation Coefficients. Direction: 2. Channel 1
STD Correlation (micro-volts)
Sessions

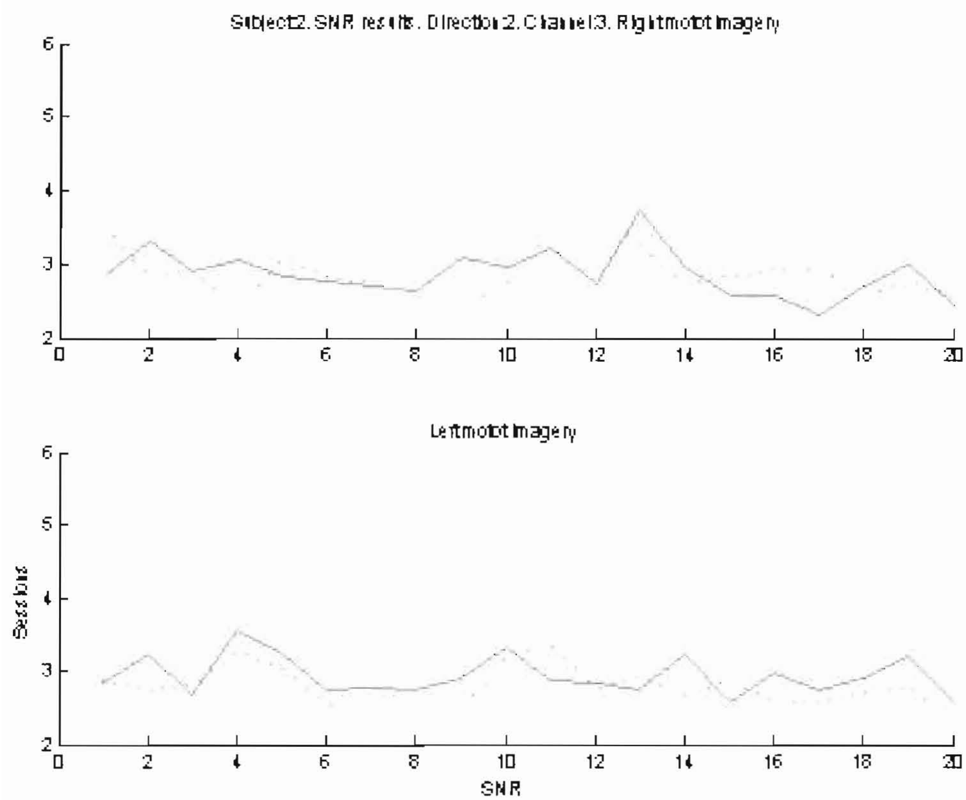

Subject 5. STD Correlation Coefficients. Direction: 2. Channel 2
x 10^-4
STD Correlation (micro-volts)
Sessions
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
0
2
4
6
8
10
12
14
16
18
20

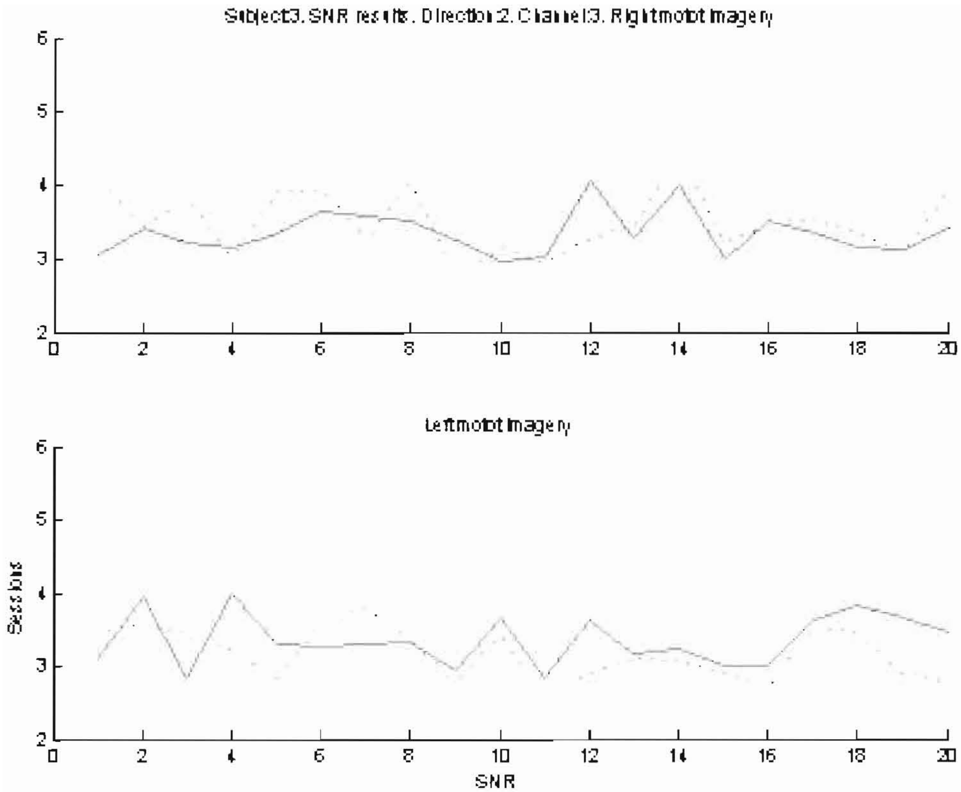

Subject 5. STD Correlation Coefficients. Direction: 2. Channel 3
x 10^-4
STD Correlation (micro-volts)
Sessions
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
0
2
4
6
8
10
12
14
16
18
20

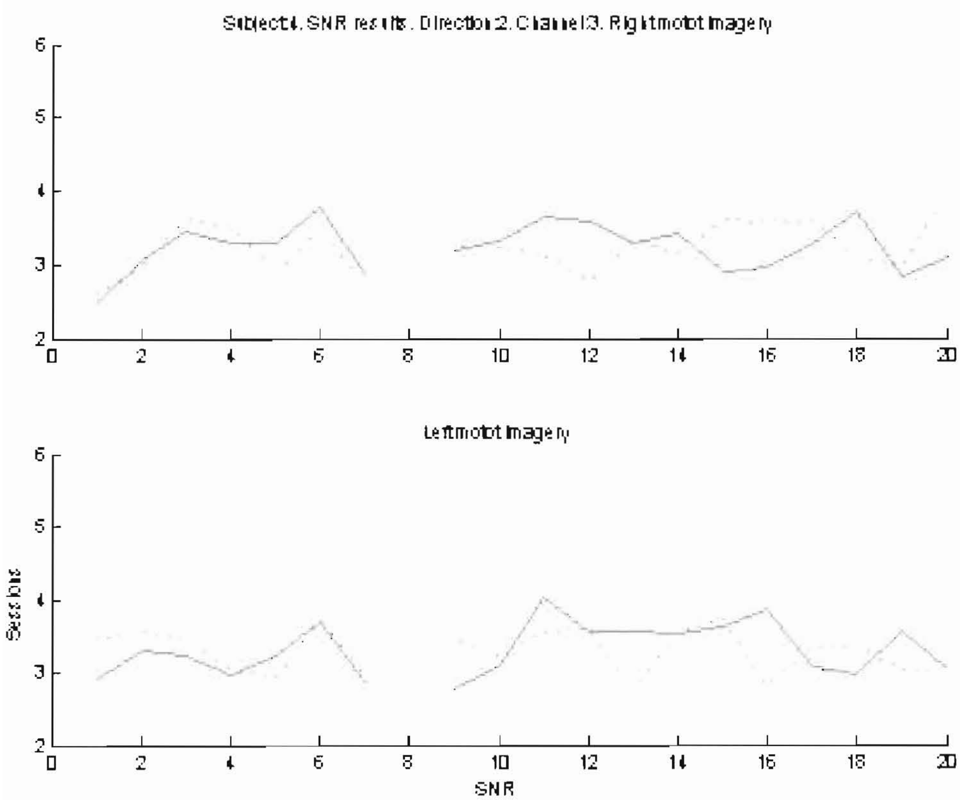
APPENDIX 8: SIGNAL TO NOISE RATIO

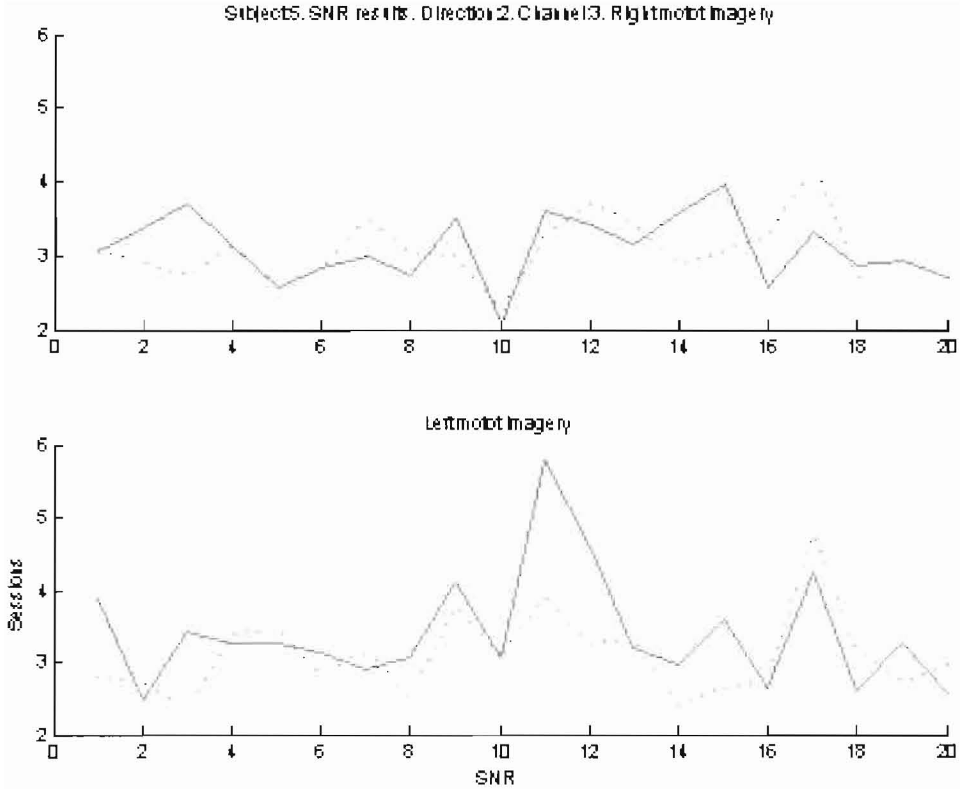
2 lines are presented on the following graphs. The dotted line represents the SNR of the left hemisphere of the scalp (channel 2) and the solid line represents the right hemisphere of the scalp (channel3). The centre of the scalp would not have given any benefits to the study, since we were trying to evaluate differences between the hemispheres.


Subject 1. SNR results. Direction 2. Channel 3. Right motor imagery
Left motor imagery
Sessions
SNR


Subject 2. SNR results. Direction 2. Channel 3. Right motor imagery
Left motor imagery
Sessions
SNR

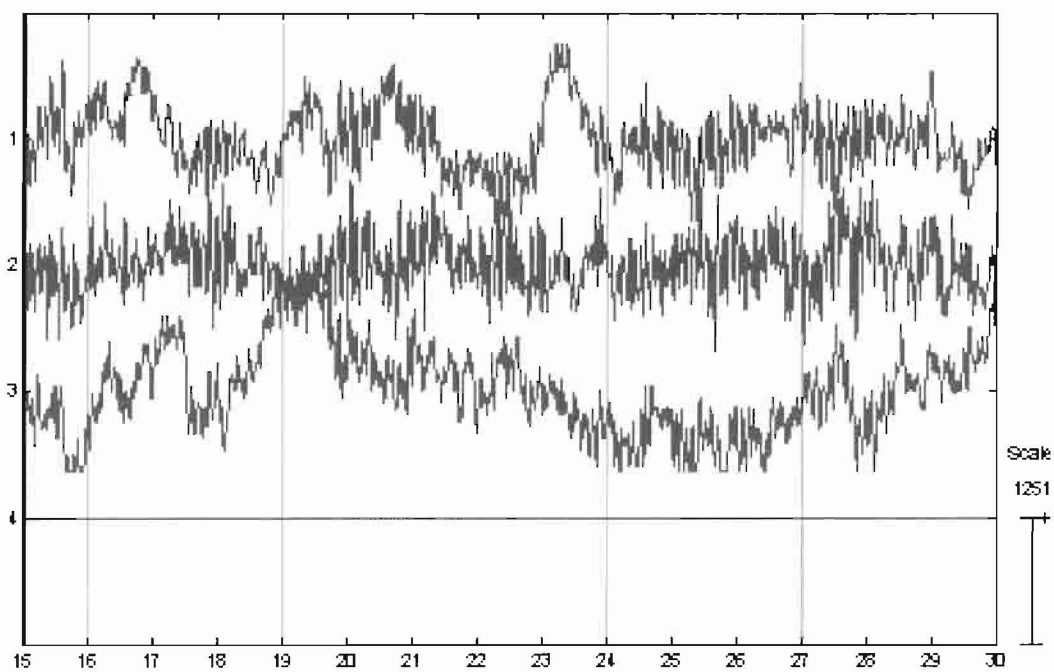

Subject3. SNR results. Direction2. Channel3. Right motot imagery
Left motot imagery
Sessions
SNR


Subject4. SNR results. Direction2. Channel3. Right motot imagery
Left motot imagery
Sessions
SNR

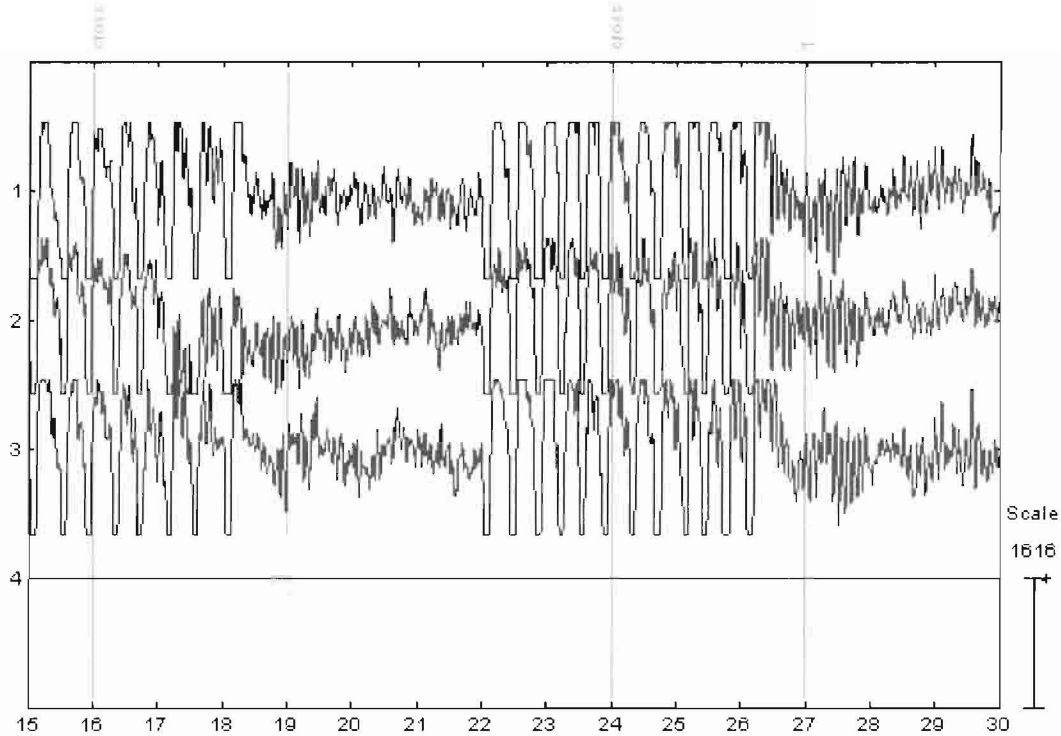

Subject5. SNR results. Direction2. Channel3. Right motor imagery
Left motor imagery
Sessions
SNR

APPENDIX 9: SUBJECT 5 EEG SIGNALS

Picture 1, in the present appendix shows the EEG signal of the first session. Picture 2 presents the exact same time and trials from the 20th session. Both pictures present the data from 100sec to 150 sec. Notice the difference in amplitude and frequency.



Picture 1, Appendix 9: Illustration of 2 trials one on each direction from subject 5, session1



Picture 2, Appendix 9: Illustration of 2 trials one on each direction from subject 5, session20

APPENDIX 10: MATLAB

Code 1: Pattern acquisition

```
clear;
cd 'c:\documents and settings\lparissh\desktop\EEGLAB'
trials=25; %number of responses form each side during a single session
numchan=3; %number of channels being analysed from the subject
numses=20; %number of sessions that each particiant took place in

subject_list={'an', 'ba', 'be', 'br', 'ig'};
for subject_number=1:size(subject_list,2)
   subject=subject_list{subject_number};
   for ses=1:numses
      x='session';  session=[x,num2str(ses)]; name_file=[subject,num2str(ses)];
      user_file=[subject,'\',subject,num2str(ses),'.csv'];
      EEG = pop_importdata( 'dataformat', 'ascii', 'data', user_file, 'setname', name_file,'srate',200,
'pnts',0, 'xmin',0, 'nbchan',0);
      EEG = eeg_checkset( EEG );
      EEG = pop_importevent( EEG,  'append', 'no', 'event', 'ppt2_both.txt', 'fields',{ 'latency',
type'}, 'skipline',1, 'timeunit',1);
      EEG = eeg_checkset( EEG );
      EEG=pop_chanedit(EEG,  'load',{ 'channels.ced', 'filetype', 'autodetect'});
      EEG = eeg_checkset( EEG );
      EEG = pop_eegfilt( EEG, 0, 30, [], [0]);
      EEG = eeg_checkset( EEG );

      EEG1= pop_epoch( EEG, {  '1'  }, [-1  2], 'newname', name_file, 'epochinfo', 'yes');
      EEG1 = eeg_checkset( EEG1);
      EEG1 = pop_rmbase( EEG1, [-1000     0]);
      EEG1 = eeg_checkset( EEG1 );
      erp1=pop_plotdata(EEG1, 1, [1:numchan] , [1:trials], [name_file,'Pattern right'], 0, 1, [0 0]);
      EEG1 = eeg_checkset( EEG1 );

      EEG2 = pop_epoch( EEG, {  '2'  }, [-1  2], 'newname', name_file, 'epochinfo', 'yes');
      EEG2 = eeg_checkset( EEG2 );
      EEG2 = pop_rmbase( EEG2, [-1000     0]);
      EEG2 = eeg_checkset( EEG2 );
      erp2=pop_plotdata(EEG2, 1, [1:numchan] , [1:trials], [name_file,'Pattern left'], 0, 1, [0 0]);
      EEG2 = eeg_checkset( EEG2 );
      close all;

      erp1_pattern=erp1; erp2_pattern=erp2;
      save([subject,'\',session,'_pattern.mat'],'erp1_pattern','erp2_pattern')
   end;
end;
```

Code 2: Data analysis

```
clear;
cd 'c:\documents and settings\lparissh\desktop\EEGLAB'
trials=25; %number of responses form each side during a single session
numchan=3; %number of channels being analysed from the subject
numses=20; %number of sessions that each particiant took place in
subject_list={'an', 'ba', 'be', 'br', 'ig'};

for subject_number=1:size(subject_list,2)
   subject=subject_list{subject_number};
   for ses=1:numses
      x='session';  session=[x,num2str(ses)]; name_file=[subject,num2str(ses)];
      user_file=[subject,'\',subject,num2str(ses),'.csv'];
      load([subject,'\session20_pattern.mat']);
     EEG = pop_importdata( 'dataformat', 'ascii', 'data', user_file, 'setname', name_file, 'srate',200,
'pnts',0, 'xmin',0, 'nbchan',0);

      EEG = eeg_checkset( EEG );
      EEG = pop_importevent( EEG,  'append', 'no', 'event', 'ppt2_both.txt', 'fields',{ 'latency',
'type'}, 'skipline',1, 'timeunit',1);
      EEG = eeg_checkset( EEG );
      EEG=pop_chanedit(EEG,  'load',{ 'channels.ced', 'filetype', 'autodetect'});
      EEG = eeg_checkset( EEG );
      EEG = pop_eegfilt( EEG, 0, 30, [], [0]);
      EEG = eeg_checkset( EEG );


      EEG1= pop_epoch( EEG, {  '1'  }, [-1  2], 'newname', name_file, 'epochinfo', 'yes');
      EEG1 = eeg_checkset( EEG1);
      EEG1 = pop_rmbase( EEG1, [-1000     0]);
      EEG1 = eeg_checkset( EEG1 );
      erp1=pop_plotdata(EEG1, 1, [1:numchan] , [1:trials], [name_file,'ERP right'], 0, 1, [0 0]);
      EEG1 = eeg_checkset( EEG1 );
      EEG2 = pop_epoch( EEG, {  '2'  }, [-1  2], 'newname', name_file, 'epochinfo', 'yes');
      EEG2 = eeg_checkset( EEG2 );
      EEG2 = pop_rmbase( EEG2, [-1000     0]);
      EEG2 = eeg_checkset( EEG2 );
      erp2=pop_plotdata(EEG2, 1, [1:numchan] , [1:trials], [name_file,'ERP left'], 0, 1, [0 0]);
      EEG2 = eeg_checkset( EEG2 );

      %loading and correlation loop set
      i=1; chan=1; dir=1;
      for dir=1:2
         for i=1:trials
            tr=ones(1,trials);
            tr(i)=0;
            for chan=1:numchan
               if dir==1
                  EEG3=EEG1;
                  EEG3 = pop_rejepoch( EEG3, tr, 0);
                  trialch{dir,i,chan}=EEG3.data(chan,:);
                  corrtr{dir,i,chan}=xcorr(erp1(chan,:),trialch{dir,i,chan});
                  corr_pattern_last{dir,i,chan}=xcorr(erp1_pattern(chan,:),trialch{dir,i,chan});
               end
               if dir==2
```

```
                EEG3=EEG2;
                EEG3 = pop_rejepoch( EEG3, tr, 0);
                trialch{dir,i,chan}=EEG3.data(chan,:);
                corrtr{dir,i,chan}=xcorr(erp2(chan,:),trialch{dir,i,chan});
                corr_pattern_last{dir,i,chan}=xcorr(erp2_pattern(chan,:),trialch{dir,i,chan});
            end
            windowsize=50; %two peaks

corr_filter{dir,i,chan}=filter(ones(1,windowsize)/windowsize,1,abs(corrtr{dir,i,chan}(:)));
[max_value{dir,i,chan}(1),max_value{dir,i,chan}(2)]=max(corr_filter{dir,i,chan}(400:1000)); %It is
from 400=0min to 1000=1min and 30sec, because we are just analysing the first min and half
after the stimulus

            windowsize=50; %two peaks
corr_pattern_filter_last{dir,i,chan}=filter(ones(1,windowsize)/windowsize,1,abs(corr_pattern_last{d
ir,i,chan}(:)));

[max_pattern_value_last{dir,i,chan}(1),max_pattern_value_last{dir,i,chan}(2)]=max(corr_pattern_f
ilter_last{dir,i,chan}(400:1000)); %Values from correlation in (1), and data representing time (2).
We take values form 400 to 1000, to creat the window between -1sec and +2sec around the
stimulus.
        end
      end
    end

    %Mean, and STD loop
for count_dir=1:2
      for count_z=1:3
        for count_i=1:trials
            max_pattern_value_corr_last(count_dir, count_i,
count_z)=max_pattern_value_last{count_dir,count_i,count_z}(1);% correlation response
            max_pattern_value_time_last(count_dir, count_i,
count_z)=max_pattern_value_last{count_dir,count_i,count_z}(2);% time response
        end

mean_max_pattern_value_corr_last(count_dir,count_z)=mean(max_pattern_value_corr_last(cou
nt_dir,:, count_z));%mean correlation value

std_max_pattern_value_corr_last(count_dir,count_z)=std(max_pattern_value_corr_last(count_dir
,:, count_z));%std correlation value

mean_max_pattern_value_time_last(count_dir,count_z)=mean(max_pattern_value_time_last(cou
nt_dir,:, count_z));%mean time vlaue

std_max_pattern_value_time_last(count_dir,count_z)=std(max_pattern_value_time_last(count_di
r,:, count_z));%std time value
      end
    end

    for count_dir=1:2
      for count_z=1:3
        %cross-correlation of all trials
        for count_i=1:trials
            for count_j=1:trials
```

```
cross_corr{count_dir,count_z,count_i,count_j}=xcorr(trialch{count_dir,count_i,count_z},trialch{cou
nt_dir,count_j,count_z});
                  max_cross_corr{count_dir,count_z,
count_i,count_j}=max(cross_corr{count_dir,count_z,count_i,count_j});
               end
            end
            %end cross correlation
         end
      end
      close all;

save([subject,'\',session,'_data.mat'],'max_pattern_value_last','mean_max_pattern_value_corr_la
st','std_max_pattern_value_corr_last','mean_max_pattern_value_time_last','std_max_pattern_val
ue_time_last')
   end;
end;
```

Code 3: Data concatenation and display

```
clear;
cd 'c:\documents and settings\lparissh\desktop\EEGLAB'
trials=25; %number of responses form each side during a single session
numchan=3; %number of channels being analysed from the subject
numses=20; %number of sessions that each particiant took place in
se=1; %start counter for sessions
alltrials=trials*numses; %number of all trials on one side
avlength=22*numses;
subject='an';% Each subject was displayed separetly

%Concatenation of the data from all the sessions
for se=1:numses
   load([subject,'\session',num2str(se),'_data.mat'])
   allmax_pattern_value_last{se}=max_pattern_value_last;
   allmean_max_pattern_value_corr_last{se}=mean_max_pattern_value_corr_last;
   allstd_max_pattern_value_corr_last{se}=std_max_pattern_value_corr_last;
   allmean_max_pattern_value_time_last{se}=mean_max_pattern_value_time_last;
   allstd_max_pattern_value_time_last{se}=std_max_pattern_value_time_last;
end

x=1:1:alltrials;
a=1:1:avlength;
y=x;
for count_dir=1:2
   for count_z=1:3
      for se=1:numses
         for i=1:trials
            timelast((se-1)*(25)+i)=allmax_pattern_value_last{se}{count_dir,i,count_z}(2); % time
response
            corrpattlast((se-
1)*(25)+i)=allmax_pattern_value_last{se}{count_dir,i,count_z}(1);%correlation value

all_sessions_mean_corr(se)=allmean_max_pattern_value_corr_last{se}(count_dir,count_z);
            all_sessions_std_corr(se)=allstd_max_pattern_value_corr_last{se}(count_dir,count_z);
```

```
all_sessions_mean_time(se)=allmean_max_pattern_value_time_last{se}(count_dir,count_z);
            all_sessions_std_time(se)=allstd_max_pattern_value_time_last{se}(count_dir,count_z);
         end
         for j=1:22
            average((se-1)*(22)+j)=allnorm_Ltwo{se}{count_dir,j,count_z};
         end
      end
% End of concatenation
      std_time=(((std(timelast)+400))/400)-1; % STD of time value used for analysis
      mean_time=(((mean(timelast)+400))/400)-1; %Mean time value used for analysis
      mean_corr=mean(corrpattlast); % Mean correlation value used for analysis

%       %Response Time Display
%       figure;plot(x,((timelast+400)/400)-1,'*',x,polyval(polyfit(x,((timelast+400)/400)-1,3),x),'-');
%       p=polyfit(x,((timelast+400)/400)-1,3)
%       xlabel('Trials');ylabel('Time (sec)');
%       title(['Subject:',subject , '. Reaction Time. Direction: ',num2str(count_dir),'.
Channel:',num2str(count_z)]);
%       axis([0  500  -0.5  2])

%Time histogram Display
%        figure;hist(((timelast+400)/400)-1);title(['Subject:',subject,'. HIST Time.
Direction:',num2str(count_dir),'. Channel:',num2str(count_z)]);xlabel('Time (sec)');ylabel('Number
of Trials at given Time');
%
%       %Correlation Coefficients Display
%       figure;plot(x,corrpattlast,'*',x,polyval(polyfit(x,corrpattlast,3),x),'-
');xlabel('Trials');ylabel('Correlation Coefficient (micro-volts)');
%       title(['Sub:',subject , '. Correlation between Pattern/trials. Direction:',num2str(count_dir),'.
Channel:',num2str(count_z)]);
%       axis([0  500  0 2E7])
%       p=polyfit(x,corrpattlast,3)% Obtaining the coefficients for the polynomial funtion
%
%       %Mean Correlation Coefficients Display
%       figure;plot(all_sessions_mean_corr);
%       xlabel('Sessions');ylabel('Mean correlation value');
%       title(['Subject:',subject , '. Mean Correlation Value. Direction: ',num2str(count_dir),'.
Channel:',num2str(count_z)]);
%       %axis([0  20  2  12E6])

      %STD Correlation Coeffients Display
      figure;plot(all_sessions_std_corr);xlabel('Sessions');ylabel('STD Correlation (MicroVolts)');
      title(['Subject:',subject , '. STD Correlation Coefficients. Direction: ',num2str(count_dir),'.
Channel:',num2str(count_z)]);
      %axis([0  20  0  5.5E6])
%
%       %Mean Time Display
%       figure;plot(((all_sessions_mean_time+400)/400)-1);xlabel('Sessions');ylabel('Mean of
Time (sec)');
%       title(['Subject:',subject , '. Mean Time. Direction: ',num2str(count_dir),'.
Channel:',num2str(count_z)]);
%       axis([0  20  0.35  1])
%
%        %STD Time Display
```

```
%       figure;plot(((all_sessions_std_time+400)/400)-1);xlabel('Sessions');ylabel('STD Time
(sec)');
%       title(['Subject:',subject , '. STD Time. Direction: ',num2str(count_dir),'.
Channel:',num2str(count_z)]);
%       axis([0 20 0.1 0.5])
  end
end
```

Code 4: SNR calculations and display

```
clear;
cd 'c:\documents and settings\lparissh\desktop\EEGLAB'
trials=25; %number of responses form each side during a single session
numchan=3; %number of channels being analysed from the subject
numses=20; %number of sessions that each particiant took place in
subject_list={'an', 'ba', 'be', 'br', 'ig'};

for subject_number=1:size(subject_list,2)
   subject=subject_list{subject_number};
   for ses=1:numses
      x='session';  session=[x,num2str(ses)]; name_file=[subject,num2str(ses)];
      user_file=[subject,'\',subject,num2str(ses),'.csv'];
      load([subject,'\session20_pattern.mat']);
     EEG = pop_importdata( 'dataformat', 'ascii', 'data', user_file, 'setname', name_file, 'srate',200,
'pnts',0, 'xmin',0, 'nbchan',0);


      EEG = eeg_checkset( EEG );
      EEG = pop_importevent( EEG,  'append', 'no', 'event', 'ppt2_both.txt', 'fields',{ 'latency',
'type'}, 'skipline',1, 'timeunit',1);
      EEG = eeg_checkset( EEG );
      EEG=pop_chanedit(EEG,  'load',{ 'channels.ced', 'filetype', 'autodetect'});
      EEG = eeg_checkset( EEG );
      EEG = pop_eegfilt( EEG, 0, 30, [], [0]);
      EEG = eeg_checkset( EEG );
      EEGorig=EEG;
%sample window widened to allow for inclusion of 100ms of noise
      EEG1= pop_epoch( EEG, {  '1'  }, [-1  3], 'newname', name_file, 'epochinfo', 'yes');%2
changed to 3 to increase the sample window.
      EEG1 = eeg_checkset( EEG1);
      EEG1 = pop_rmbase( EEG1, [-1000     0]);
      EEG1 = eeg_checkset( EEG1 );
      erp1=pop_plotdata(EEG1, 1, [1:numchan] , [1:trials], [name_file,'ERP right'], 0, 1, [0 0]);
      EEG1 = eeg_checkset( EEG1 );
      EEG2 = pop_epoch( EEG, {  '2'  }, [-1  3], 'newname', name_file, 'epochinfo', 'yes');
      EEG2 = eeg_checkset( EEG2 );
      EEG2 = pop_rmbase( EEG2, [-1000     0]);
      EEG2 = eeg_checkset( EEG2 );
      erp2=pop_plotdata(EEG2, 1, [1:numchan] , [1:trials], [name_file,'ERP left'], 0, 1, [0 0]);
```

```
        EEG2 = eeg_checkset( EEG2 );
        close all;
        %loading trials and RMS loop set
        i=1; chan=1; dir=1;
        for dir=1:2
            for trial=1:trials
                tr=ones(1,trials);
                tr(trial)=0;
                for chan=1:numchan
                    if dir==1
                        EEG3=EEG1;
                        EEG3 = pop_rejepoch( EEG3, tr, 0);
                        rawdata=EEG3.data(chan,:);
                        [x,y]=max(rawdata(1:400));
                        peak_raw{subject_number,ses,dir,trial,chan} = [x,y];
                        u=rawdata(300/5+y:300/5+y+100/5);
                        noise_raw{subject_number,ses,dir,trial,chan} = sqrt(sum(u.*conj(u))/size(u,2));
%calculates the rms from 300 to 400ms after the peak

snr_raw{subject_number,ses,dir,trial,chan}=x/noise_raw{subject_number,ses,dir,trial,chan};
                        plot_snr{subject_number,dir,chan}((ses-1)*trials +
trial)=snr_raw{subject_number,ses,dir,trial,chan};
                    end %if dir==1
                    if dir==2
                        EEG3=EEG2;
                        EEG3 = pop_rejepoch( EEG3, tr, 0);
                        rawdata=EEG3.data(chan,:);
                        [x,y]=max(rawdata(1:400));
                        peak_raw{subject_number,ses,dir,trial,chan} = [x,y];
                        u=rawdata(300/5+y:300/5+y+100/5);
                        noise_raw{subject_number,ses,dir,trial,chan} = sqrt(sum(u.*conj(u))/size(u,2));
%calculates the rms from 300 to 400ms after the peak

snr_raw{subject_number,ses,dir,trial,chan}=x/noise_raw{subject_number,ses,dir,trial,chan};
                        plot_snr{subject_number,dir,chan}((ses-1)*trials +
trial)=snr_raw{subject_number,ses,dir,trial,chan};
                    end %if dir==2
                end %for chan=1:numchan
            end %for trial=1:trials
        end %for dir=1:2
    end; %for ses=1:numses
end; %for subject_number=1:size(subject_list,2)
save('all_raw.mat','plot_snr','peak_raw','noise_raw','snr_raw');
```

Code for the SNR filter and display

```
load c:/all_raw.mat
trials=25;
trim_num=2;
for subject=1:5
   for direction=1:2
      for channel=1:3
         for session=1:20
            sub_set=plot_snr{subject,direction,channel}((session-1)*trials+1:session*trials);
            sub_mean=mean(sub_set);
                   %Filtering Outliers loop
            for i=1:trim_num
               [min_set,min_index(i)]=min(sub_set);
               sub_set(min_index(i))=sub_mean;
               [max_set,max_index(i)]=max(sub_set);
               sub_set(max_index(i))=sub_mean;
            end;
                   %Computing the mean value per session
            sub_set(max_index)=0;
            sub_set(min_index)=0;
            sub_mean=mean(sub_set)*trials/(trials-2*trim_num);
            sub_set(max_index)=sub_mean;
            sub_set(min_index)=sub_mean;
            fit_set{subject,direction,channel}((session-1)*trials+1:session*trials)=sub_set;
            all_means{subject,direction,channel}(session)=sub_mean;
         end
      end
   end
end
% SNR Display loop
for subj=1:5
      figure;subplot(2,1,1);hold on;plot(all_means{subj,1,2},':');plot(all_means{subj,1,3},'-');
title(['Subject:',num2str(subj),'. SNR results. Direction:',num2str(direction),'.
Channel:',num2str(channel),'. Right motot imagery']);axis([0  20  2  6]);hold off;
   subplot(2,1,2);hold on;plot(all_means{subj,2,2},':');plot(all_means{subj,2,3},'-');title('Left motot
imagery');axis([0  20  2  6]);hold off;
    title(['Left motot imagery']);
    xlabel('SNR');ylabel('Sessions');
    filename=['SNRimages\','snrcc',num2str(subj),
'd',num2str(direction),'ch',num2str(channel),'.png'];
    print('-dpng',filename, '-r60');
   %close all
end
```