NeuroMonitor Ambulatory EEG Device: Comparative Analysis and Its Application for Cognitive Load Assessment

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***Abstract*— We have previously presented a wireless ambulatory EEG device (NeuroMonitor) to non-invasively monitor prefrontal cortex scalp EEG activity in real-life settings. This paper discusses analysis and application of data acquired using this device. We assess the device data against a commercially available, clinical grade Neuroscan SynAmps RT EEG system. For the comparison, temporal statistical measures and Power Spectral Density (PSD) are computed for the simultaneous recordings from both devices from (nearly) identical electrode locations. Although the analog signal processing, sampling, and data recording specifications are slightly different for these devices (e.g., filter specifications, ADC - NeuroMonitor: 16 bit and Neuroscan: 24 bit, electrodes - NeuroMonitor: GS26 Pre-gelled Disposable, Neuroscan: Ag/AgCl reusable EEG disc electrodes), the temporal signals and the PSD of two devices had sufficient correlation. The paper also describes pilot data collection for a test protocol to determine cognitive load using the NeuroMonitor device. For analyzing attention levels for 5 different tasks, EEG rhythms (Alpha, Beta and Theta) are extracted and cognitive load index (CLI) is computed. Results show variations in the PSD of these rhythms with respect to corresponding expected cognitive loads in attention-related and relaxed tasks. This study validates the NeuroMonitor ambulatory EEG device data and shows a use-case for real-life cognitive load studies.**

I. INTRODUCTION

Cortical brain activity can be recorded non-invasively using state-of-the art ambulatory EEG technology. Most of the commercially available wireless EEG data systems contain a large number of multichannel electrodes. While these are excellent choices to provide the complete brain activity data in a laboratory setting, these are rarely practical to be deployed for daily activity monitoring [1, 2].

NeuroMonitor is a miniature (size: 2.2” x 0.8” x 0.36”), lightweight (27 g without enclosure), low-power (active mode: 32 mA), two-channel referential montage based EEG device that is practically deployable in real-life settings and can wirelessly transmit data (using Bluetooth), while being concealed within head accessories like a cap/headband [3, 4]. The device is designed using Programmable System-on-Chip (PSoC 3 CY8C38, Cypress Semiconductor) which integrates a microcontroller unit (MCU), 2 KB of RAM, configurable analog (op-amp, Register, Capacitor) and digital (ADC, DAC, filters, UART, USB) peripherals on a single chip. The analog front end of the device consists of a low-power instrumentation amplifier, a notch filter (f_c = 60Hz), a 2nd-order Chebyshev-I low-pass filter cascaded with a 2nd-order low-pass (f_c = 125Hz) and high pass filter (f_c =0.16Hz). The 16-bit Analog to Digital converter (ADC) of the PSOC samples EEG signal from two channels at 256 sps and transmits the digitized signal wirelessly through Bluetooth at baud rate of 115.2 kbps in online mode. In the offline mode, if selected, data is saved in the SD card on the board.

Neuroscan SynAmps RT (Compumedics Neuroscan USA, Ltd. Charlotte, NC, USA), on the other hand, is widely accepted for research use, commercially available, 70 channel amplifier system with low noise 24-bit ADC, input impedance greater than 10 GΩ and high Common Mode Rejection ratio of 110 dB [5].Fig. 1 shows the photographs of the prototyped 2-channel NeuroMonitor device, concealed within a headband, and the amplifier system for Neuroscan. As shown in Fig. 1(c), Neuroscan uses SynAmps RT amplifier system which allows access to 70 channels (64: monopolar, 4: bipolar and 2 high-level input channels) for full coverage of the scalp. The EEG signals acquired with Ag/AgCl disc electrodes are amplified using a Neuroscan SynAmps RT system and processed using CURRY 7 Neuroimaging Suite (Compumedics USA, Inc., Charlotte, NC, USA).

The technical specifications of SynAmps RT amplifier for

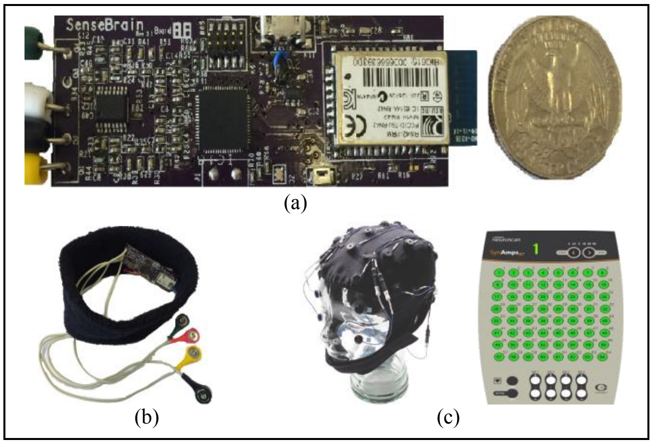

Figure 1. (a) Prototype of Ambulatory NeuroMonitor platform beside a US quarter. (b) Concealed within headband (c) SynAmps RT amplifier system [2].

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data acquisition are configurable. For this study, data is recorded from 2 channels (monopolar montage) at sampling frequency of 500 sps with 24-bit quantization level. For near one-to-one comparison with NeuroMonitor EEG data, the acquired data with SynAmps RT system is down sampled to 256 sps. The CURRY software also provides a visual display for impedance testing across all the channels, so during data acquisition, the average impedance for the channels of interest (FP1 and FP2) is maintained less than 10 kΩ. However there are no means to measure the electrode impedance with the existing NeuroMonitor device.

II. METHODS FOR EEG DATA VALIDATION

A. Data Acquisition

EEG data has been recorded from four subjects with both devices placed side to side on the prefrontal cortex at FP1 and FP2 channel locations (based on 10-20 International electrode system). Both channels were referenced to ~FPz location (center of the forehead) with the ground electrode on the left mastoid. Data was recorded in a magnetically shielded room (MSR) with dim light for ~2 minutes. For the first 60 seconds, subjects were in the relaxed state with their eyes closed. During the next 60 seconds, subjects were instructed to blink with 5 sec hiatus. NeuroMonitor uses gel based (GS26 Pre-gelled sensor, Bio-medical Instruments) disposable sensors that can only be used on scalp without hair (such as prefrontal cortex) in contrast to EEG disc electrodes used for Neuroscan.

B. Signal Processing Procedure

EEG signals from both devices were digitally filtered from 1-40 Hz using FIR filters in EEGLAB [6]. Simultaneous recordings from the two devices were compared using frequency–domain and time-domain measures. Power Spectral Density (PSD) was computed for each channel using Welch's method in MATLAB (MathWorks, Natick, MA). Welch's method gives the power spectral density estimate using Hamming window of length 512 over FFT length of 1024 with 50% window overlap. Fig. 2 represents the average PSD (four datasets) for FP1 channel from both devices during blink and non-blink sessions. As evident from the figure, PSD of NeuroMonitor data is comparable, but higher in magnitude than Neuroscan. This difference is due to different electrode impedances and amplifier gains.

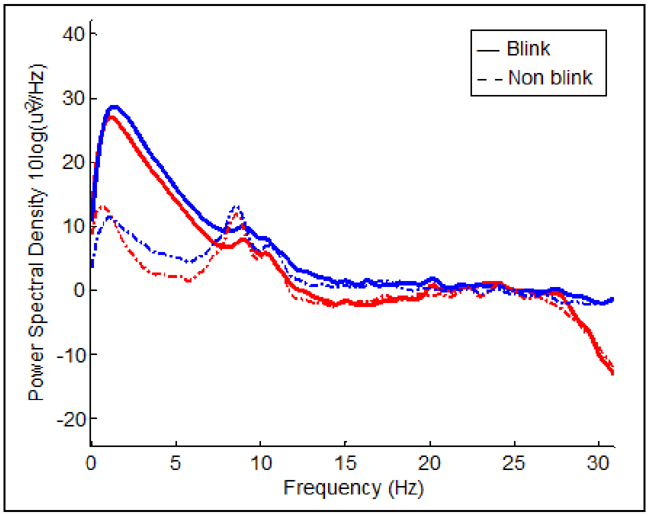


Figure 2. Average Power Spectral Density of FP1 channel from both devices with blink and non-blink conditions. Blue : NeuroMonitor and Red: Neuroscan

Linear correlations and distributions between two signals were analyzed using *corrcoef* and *kurt* functions in MATLAB. Average Kurtosis and correlation coefficient are tabulated in Table 1 (only FP1 results are shown).

TABLE I. TIME DOMAIN MEASURES FOR BOTH DEVICES FOR FP1

Device	**Kurtosis**		**Correlation Coef.**	
	Blink	***Non-blink***	***Blink***	***Non-blink***
NeuroMonitor	17.68	1.125	0.8813	0.7660
Neuroscan	19.45	0.8075		

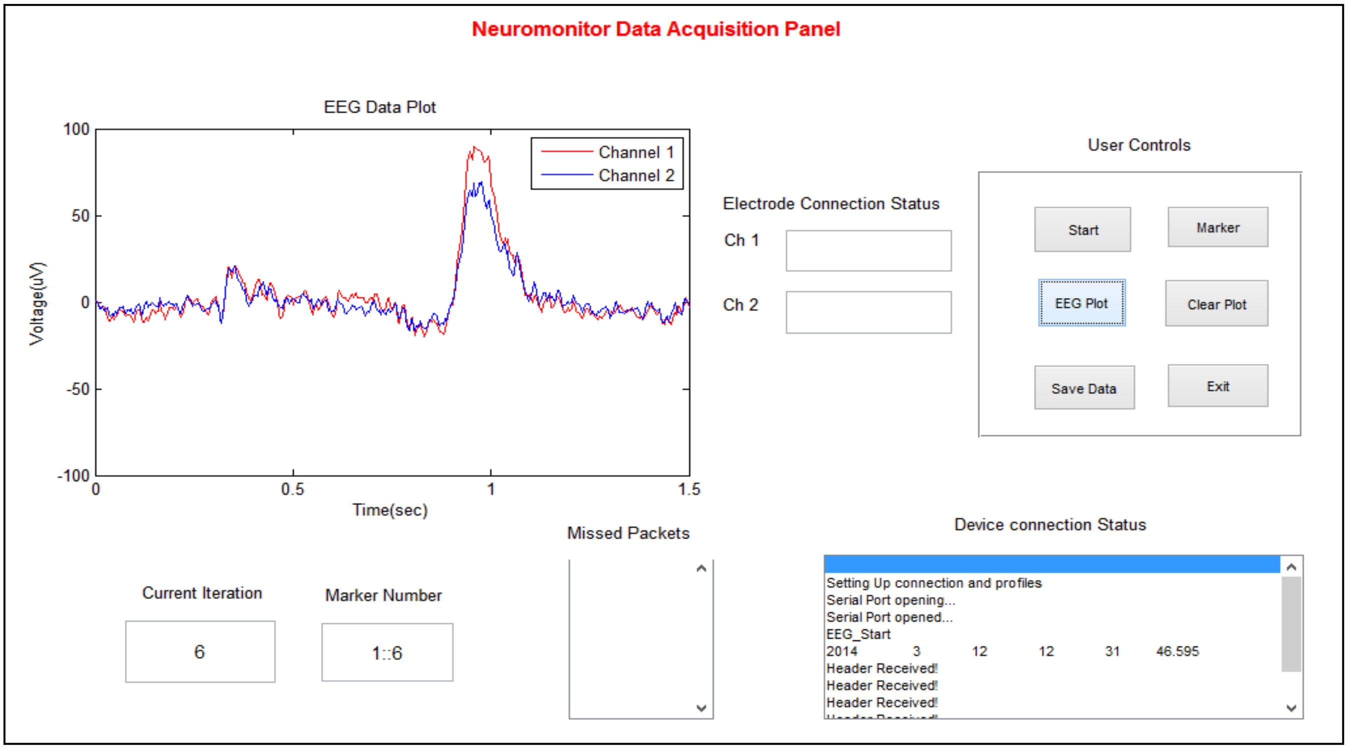
C. Data Validation

One major difference between NeuroMonitor and Neuroscan is that the former transmits data wirelessly. To ensure that NeuroMonitor is transmitting signals reliably through Bluetooth, all data packets are marked with headers of packet count. At the receiver side in MATLAB, packet count is checked and in case if there is any loss of data, the user is notified by the Missed Packets count in Graphical User interface (GUI) panel of data acquisition software, refer Fig. 3. In PSOC, 16-bit ADC samples the signals at 256 sps and saves the sampled data in two buffers of size 512 bytes each. Before sending the data through UART, header of 22 bytes is appended in each buffer's data, making the packet size to be transmitted of 534 bytes. At the receiver side in MATLAB, 534 bytes of data is received and processed. User can insert markers during data acquisition to record important events. In case of loose connection of Channel 1 (FP2) and Channel 2 (FP1) electrodes, warning is displayed in the GUI along with the marker count and current loop iteration. Fig. 3 shows an EEG recording session of 1.5 seconds (eye-blink at 1s can be noticed) with 1 marker pressed during acquisition.

III. APPLICATION FOR COGNITIVE LOAD ASSESSMENT

A. Data Acquisition Protocol

In this section, application of NeuroMonitor has been explored for analyzing different cognitive states of the subjects. The experiment protocol includes recordings from 4 subjects who are instructed to do 5 tasks. Each task is intended for 2 minutes, starting with Task 1 to relax that sets the baseline for EEG. In Task 2, subject is asked to solve the given Math Quiz to engage them, followed by Task 3 to listen to music. During Music Listening Task, the subject listens to 'Weightless' song, which is considered as one of the most relaxing tunes in a recent study (Scientists at Mindlab institution, Neuromarketing company) to reduce anxiety and stress. Task 4 is to play a game on the Computer Screen for 2 minutes and in the last Task 5, the subject is again relaxed and sits idle (in order to set the baseline again). The average duration of data acquisition is 13 minutes.



Current Iteration: 6

Marker Number: 1::6

```
Setting Up connection and profiles
Serial Port opening...
Serial Port opened...
EEG_Start
2014        3        12        12        31        46.595
Header Received!
Header Received!
Header Received!
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Figure 3. GUI Panel of NeuroMonitor Data Acquisition software in MATLAB depicting 1.5 seconds of recording session.

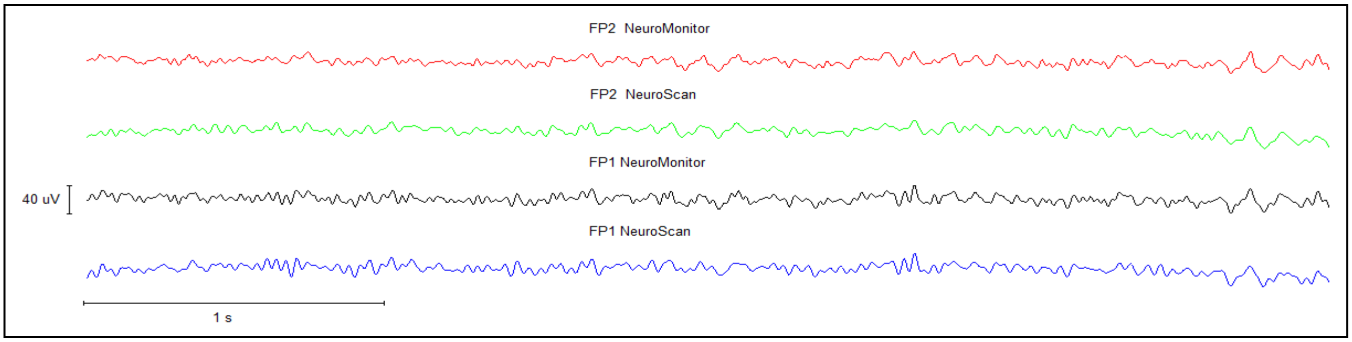

Figure 4. Section of EEG data recordings for around 4 sec with Neuroscan and NeuroMonitor systems. Blue and Green: FP1 and FP2 channel data from Neuroscan. Black and Red : FP1 and FP2 channel data from NeuroMonitor.

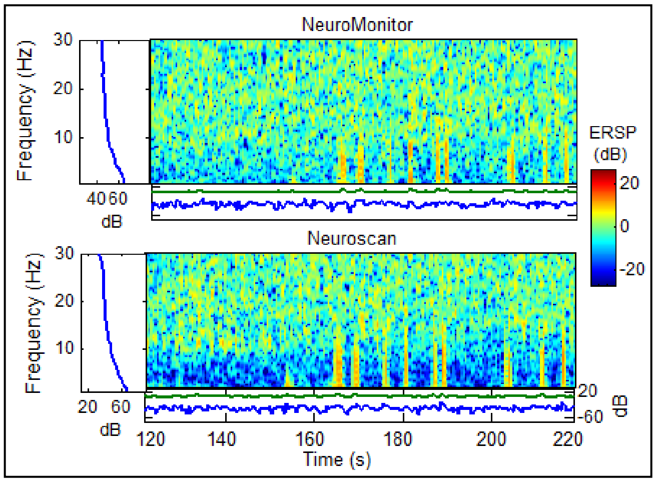

Figure 5. Time-Frequency analysis over a section (100 seconds) of Subject 1's EEG data (blink and non-blink) from FP1 channel.

IV. RESULTS

A section of data acquired by the two devices are compared in Fig. 4 that suggests the time recordings from Neuroscan are cleaner and smoother in comparison with NeuroMonitor device. Fig. 5 shows time-frequency relation between two devices for one subject. NeuroMonitor device uses unshielded electrode leads, whereas Neuroscan System uses shielded leads that might contribute to increased noise to NeuroMonitor signals.

For Cognitive Load assessment for different tasks, Alpha waves (8-13 Hz), Beta waves (13-30 Hz) and Frontal Line Theta waves (4-8 Hz) are extracted from Fast Fourier Transform (FFT) of EEG signal from both channels using MATLAB. Average PSD is computed for the Alpha, Beta and Theta bands for all 5 tasks for each subject. As the Frontal Lobe is more associated with analytical thinking, problem solving and attention levels [7], the variations in power is expected as per the tasks. Task 1 (Rest), Task 3 (Music) and Task 5 (Rest) are framed as relaxing task while Task 2 (Math) and Task 4 (Game), demand attention. Beta power increases with the engagement, so is the Frontal Line Theta [8], but Alpha power decreases. To quantify the power differences during different activities, Cognitive Load Index (CLI) is computed by using:

$$\mathrm{CLI} = \frac{\text{Average Beta Power} + \text{Average Theta Power}}{\text{Average Alpha Power}} \qquad (1)$$

Fig. 6 represents the CLI values for each subject whereas Fig. 7 illustrates the intersubject differences in EEG waves for each task. All subjects except Subject 4 seem to be comparatively more engaged in the Task 2 and Task 4 than the other three tasks. Subject 4 expressed his concern of mind wandering (during relax tasks) at the end of recording session. Statistical significance difference (p=0.012) between the CLI for different tasks is found using Repeated Measures ANOVA test at 95% confidence interval (excluding S4 dataset) [9]. Furthermore, pairwise comparisons between the CLI's of tasks (for FP2) are evaluated using SNK test in Sigma Plot (Systat Software Inc., San Jose, CA). CLI for Task 2 (μ = 2.060, σ = 0.0700) and Task 4 (μ = 1.997, σ = 0.1580) are observed to be significantly different from Task 1 (μ = 1.670, σ = 0.183), Task 3 (μ = 1.697, σ = 0.0681), and Task 5 (μ = 1.703, σ = 0.142) with p values of 0.032, 0.032, 0.021 (for Task 2) and 0.053, 0.047, 0.022 (for Task 4), respectively. However, no significant difference is found between Task 2 and Task 4 (p = 0.557), which correlates the proposed CLI analysis against the protocol.

V. CONCLUSIONS

This study deals with the comparative analysis of the ambulatory, low power, wireless, 2-channel NeuroMonitor platform that is designed to measure brain activity in real-life settings. Comparison between EEG data of this device and that of a commercially available Neuroscan SynAmps RT system were performed. Frequency-power spectrum and time-domain analysis on the recording show that although the data is slightly noisy in comparison with Neuroscan system but is qualitatively similar. Furthermore, application of NeuroMonitor platform for measuring cognitive load was explored. The study showed that based on the changes in Beta, Frontal Midline Theta and Alpha wave power, cognitive load index can be generated to monitor brain engagement activity in real-life settings.

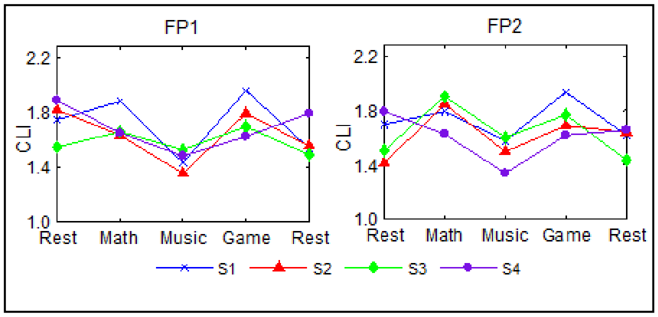

Figure 6. Cognitive load Index for all subjects Sx (x- Number) performing 5 tasks from the two channel locations of NeuroMonitor.

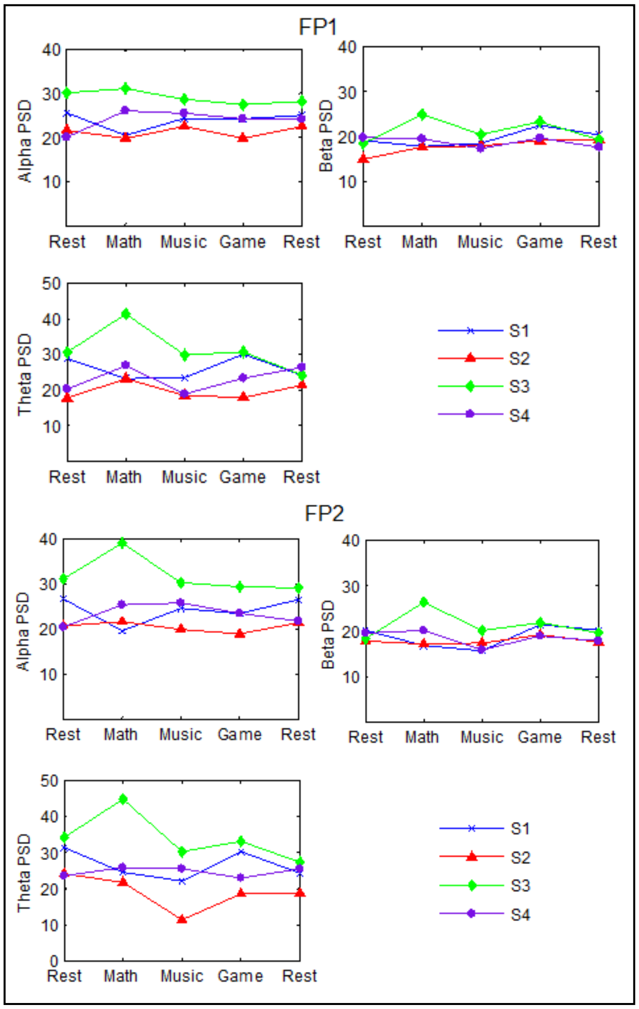

Figure 7. Average Alpha , Beta and Theta PSD (10log (μV)^2/ Hz) for all subjects Sx (x- Number) during different tasks for both channels.

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