Resting-state EEG recorded with gel-based versus consumer dry electrodes: spectral characteristics and across-device correlations

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Abstract.

Recordings of electroencephalographic (EEG) rhythms and their analyses have been instrumental in basic Neuroscience, clinical diagnostics, and the field of brain-computer interfaces (BCIs). While in the past such measurements have been conducted mostly in laboratory settings, recent advancements in dry electrode technology pave way to a broader range of consumer and medical application because of their greater convenience compared to gel-based electrodes. Here we conducted resting-state EEG recordings in eleven healthy participants using two dry-electrode devices, the Neiry Headband and the Muse Headband, and a standard gel electrode-based system, the NVX. We examined signal quality for various spatial and spectral ranges which are essential for cognitive monitoring and consumer applications. Distinctive characteristics of signal quality were found, with the Neiry Headband showing sensitivity in low-frequency ranges and successfully replicating the modulations of delta, theta and alpha power corresponding to the eyes-open and eyes-closed conditions, and the NVX system excelling in capturing high-frequency oscillations. The Muse Headband had several limitations in signal quality. We suggest that while dry-electrode technology appears to be appropriate for the EEG rhythm-based applications, the potential benefits of these technologies in terms of ease of use and accessibility should be carefully weighted against the capacity of each concrete system.

1. Introduction

Electroencephalography (EEG) has been an invaluable tool in neuroscientific research, clinical diagnostics, and brain-computer interface (BCI) applications. Conventionally, EEG recordings have relied on wet gel-based electrodes which necessitate conductive

gel application, diligent maintenance, wired digital amplifiers, and a direct computer connection for data storage. However, recent advancements in dry electrode technology have offered a promising alternative, reducing the complexities posed by conventional gel electrodes. These novel dry electrode systems are designed to be user-friendly, opening new possibilities for improving the overall user experience and real-world EEG applications outside the restrictions of laboratory settings (Niso et al., 2023).

The quality of EEG signal acquisition is of paramount importance in any application. Signal integrity directly impacts the accuracy and reliability of EEG-based studies, including cognitive state monitoring, emotion recognition, and motor control research, among others. Therefore, rigorous validation and comparison of the signal quality between the emerging dry electrode systems and conventional gel electrodes are crucial to understanding their potential benefits and drawbacks.

Particular emphasis should be placed on evaluating the quality of capturing resting-state EEG, rather than focusing solely on responses evoked by stimuli. This distinction is crucial for consumer EEG applications that center around cognitive monitoring. Resting-state EEG data, owing to its capacity for signal processing and analysis, can unveil intricate patterns tied to attention, memory, and emotional states (Katahira et al., 2018; Bitner and Le, 2022; Sun and Yeh, 2017; Bajada and Bonello, 2021; Trejo et al., 2015; Myrden and Chau, 2017). This, in turn, may allow users to track their cognitive well-being over time, optimize their daily routines, and make well-informed decisions regarding lifestyle choices that have the potential to impact cognitive performance.

In this study, we conducted resting-state EEG recordings using two modern dry-electrode devices: the Neiry Headband by Neiry LLC, Russia, and the Muse Headband by InterAxon LLC, Canada. Additional consumer devices will be evaluated with the same method upon availability. The Neiry Headband is a novel commercially available device developed for working with EEG-based paradigms based on EEG spectral characteristics. There have been no previous studies validating the signal quality of the Neiry Headband or using Neiry Headband as a recording device for other research purposes.

The second device that was available to us, the Muse Headband, is a widely used commercial device intended for aiding meditation and sleep. Several studies have investigated its signal quality. These studies have shown that, on the one hand, it could successfully capture typical EEG spectral characteristics, such as the alpha spectral peak. However, on the other hand, it exhibited low reliability in terms of repeatability of measures conducted on different days (Ratti et al., 2017). Additionally, the Muse Headband struggled to reproduce typical brain oscillations and was susceptible to the influence of artifacts (Przegalinska et al., 2018). These reported drawbacks of the Muse Headband contributed to our conservative expectations for the Neiry Headband, as well.

Despite certain limitations compared to the medical-grade systems, the Muse Headband has demonstrated its effectiveness for ERP research (Krigolson et al., 2017). Additionally this device has found applications in various areas, including predicting task performance (Papakostas et al., 2017), human stress classification (Asif et al.,

2019), emotion recognition (Bano et al., 2022), perception of mental stress (Arsalan et al., 2019), and other purposes.

Consequently, we opted to use the Muse Headband as a point of comparison to assess whether the signals obtained from the Neiry Headband exhibited similar properties. To serve as a control device representative traditional EEG recordings, we selected the NVX EEG System (MCS, Russia) with gel electrodes, as it fulfilled the necessary criteria for a standard medical EEG recording device.

Consistent with the previous validation studies conducted with the use of other devices (Przegalinska et al., 2018; Ratti et al., 2017; Wyckoff et al., 2015; Cannard et al., 2021; Marini et al., 2019; Kam et al., 2019; Radüntz, 2018), the present study established three measures of signal quality. First, the increase in alpha power was examined during eyes-closed compared to eyes-open conditions. Second, the power correspondence in the standard frequency bands was assessed in comparison to the gel apparatus. Finally, the correlation of measures of spectral power between the devices was investigated.

2. Methods

2.1. Participants

Eleven healthy volunteers (five males, six females, mean age 26.3) participated in this study. The participants had normal or corrected-to-normal vision and provided written informed consent, following the ethics protocol approved by the Ethics Committee of Skolkovo Institute of Science and Technology (Protocol No.9 of Institutional Review Board, June 22, 2022).

2.2. Data acquisition

During the experiment, participants were seated comfortably and asked to undergo two phases of EEG recording. The first phase involved a five-minute session with eyes open, followed by an additional five-minute session with eyes closed.

The resting-state recordings were obtained using three different devices in the following sequence: Neiry Headband (Neiry LLC, Russia), Muse Headband (InterAxon LLC, Canada), and NVX-36 amplifier with gel-based Ag/Cl wired electrodes (Medical Computer Systems Ltd., Russia). The Neiry Headband is a soft band placed around the head, equipped with four dry EEG electrodes (T3, T4, O1, O2), each containing 25 pogo pins (spring-loaded electric connectors). The reference and ground electrodes are positioned frontally. The Muse system uses electrodes located similarly to Fpz, AF7, AF8, TP9, and TP10, with electrode Fpz serving as the reference electrode. In the NVX system, the electrode locations were comparable to those in the Neiry Headband (T3, T4, O1, O2), and Fp1-Fp2 electrodes were used for referencing, while ground electrode was placed as Fpz. The choice of reference and ground electrodes in NVX closely replicated the setup in Neiry Headband.

During the recordings, the default sampling rates for the portable devices were as follows: 250 Hz for the Neiry Headband, 256 Hz for the Muse Headband, and 250 Hz for the NVX system. To ensure optimal signal quality in the recordings, electrode impedance was checked before starting the EEG recording, ensuring that it was below 50 kΩ for NVX and below 500 kΩ for Neiry Headband. As for the Muse Headband, direct access to impedance values was not possible, but the available indicators showed that the impedance level was satisfactory.

2.3. EEG processing

The data analyses were performed using MNE Python software (Gramfort et al., 2013) along with other Python libraries. After importing the recorded data into MNE Python, the Muse recordings were resampled at 250 Hz. Subsequently, the data underwent high-pass filtering from 0.5 Hz using an overlap-add Finite Impulse Response (FIR) filter. To conduct spectral analysis on the time series from each channel, we computed the Power Spectral Density (PSD) using Welch's method (Welch, 1967).

Next, we extracted the mean logarithm of PSD (log PSD) values for several frequency bands (delta: 1.5-3.5 Hz, theta: 4–7.5 Hz, alpha: 8–12 Hz, low beta: 13–16 Hz, beta: 13–21 Hz, high beta: 21–32 Hz, gamma: 32-40 Hz) at each electrode site for further analysis.

2.4. Statistical analysis

The statistical analyses employed in this study utilized a repeated-measures, within-subject Analysis Of Variance (ANOVA) with participants considered as a random variable and *Device*, *Condition* and *Channel group* treated as within-subject factors. Since the portable devices allow to record activity only from four sensors, we did not examine signal quality in terms of spatial resolution and merged the features within the anterior (T3 and T4 for Neiry Heabdand and NVX, AF7 and AF8 for Muse) and posterior sites (O1 and O2 for Neiry Headband and NVX, TP9 and TP10 for Muse). To conduct post-hoc pairwise comparisons, t-tests were utilized, and a Bonferroni correction was implemented to account for multiple comparisons.

3. Results

3.1. Resting-state EEG

In Figure 1, 10-s samples of resting-state EEG data are depicted for one subject for the eyes-open and eyes-closed conditions. Data acquired from three different devices are shown. Upon a visual examination, the presence of alpha spindles is clear during the eyes-closed condition for all three devices. However, for the Muse recordings (Fig. 1, 3.b), these alpha spindles have a lower amplitude compared to the other devices.

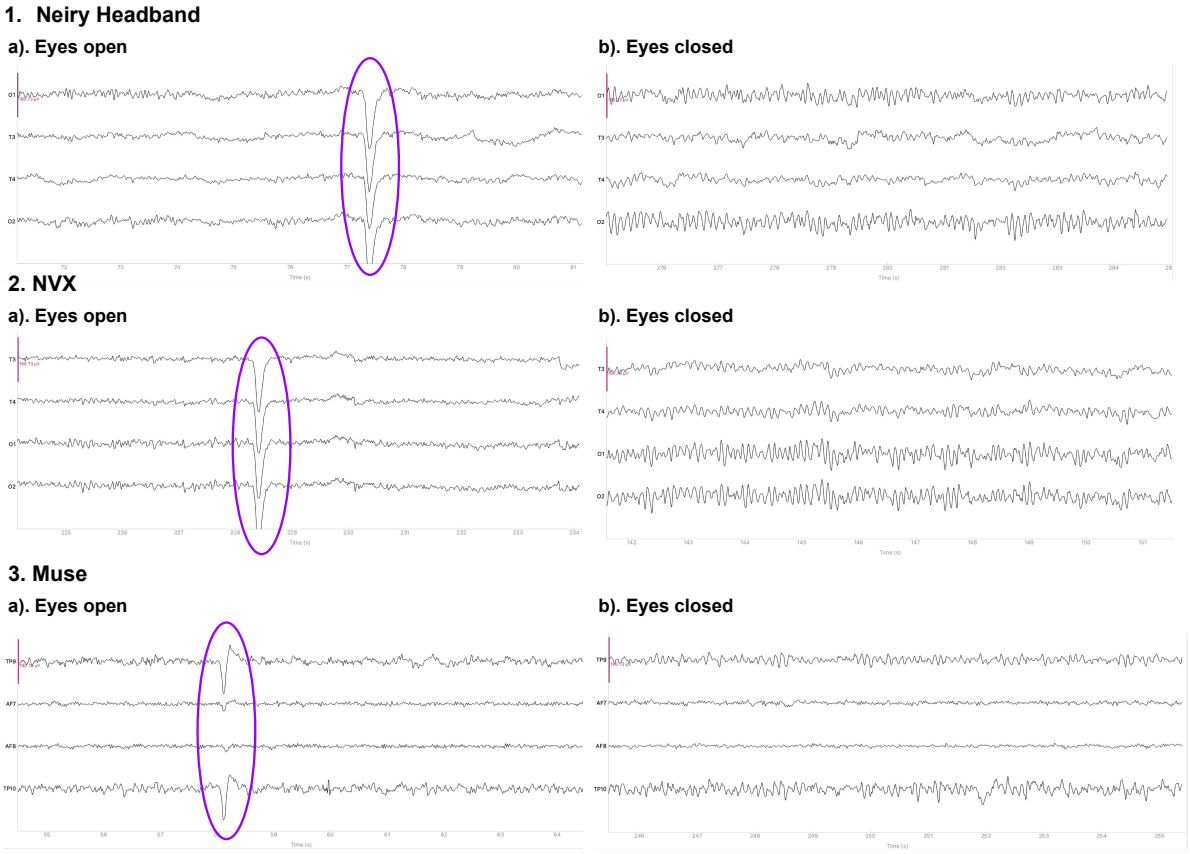

Figure 1: Representative samples of the recordings with the Neiry Headband (1), NVX (2) and Muse (3) devices for the eyes-open and eyes-closed conditions. The purple ovals mark the typical eye-blink artifacts. The y-limit is set to ±190.73 mV for all graphs. The signal was bandpass-filtered from 0.5 to 30 Hz for visualization.

3.2. Spectral analysis

Figure 2 shows the across-participant average of log PSD, clearly showing an increase in alpha power when the eyes were closed.

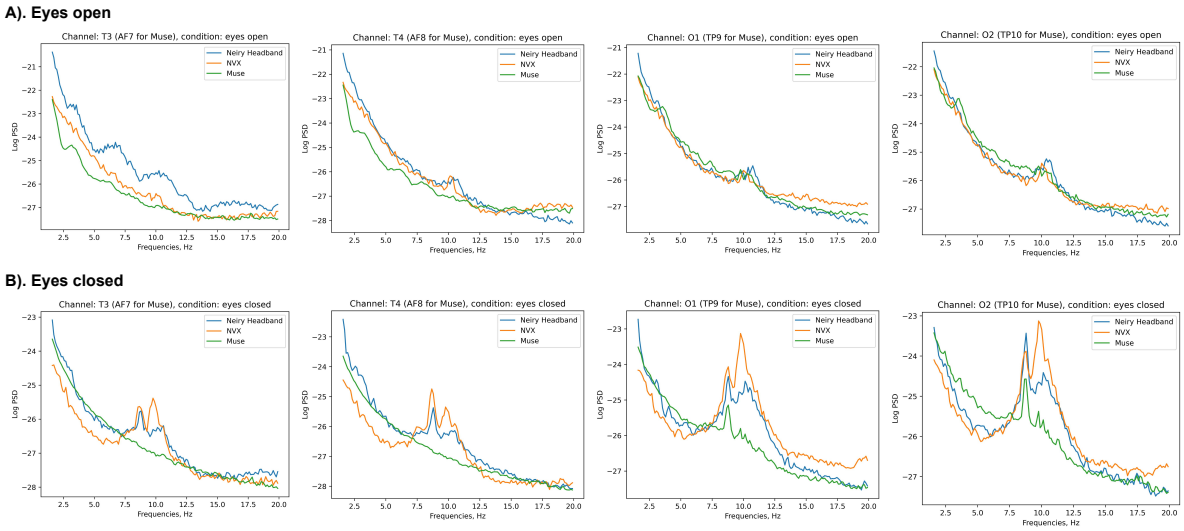

Figure 2: Across-subject (N=11) averages of log PSD demonstrating the difference in alpha power during eyes-open (A) versus eyes-closed (B) conditions

A repeated measures ANOVA was conducted to examine the effects of device, condition and channel group on the mean value of log PSD in a given frequency range.

The results showed that the choice of a device did not have a significant main effect on the delta power ($F(2, 20) = 2.611$, $p = 0.0983$) (Fig. 3, A). However, both condition ($F(1, 10) = 63.3793$, $p < 0.001$) and channel group ($F(1, 10) = 27.2044$, $p < 0.001$) had significant main effects. Moreover, there were significant interactions observed between the device and condition ($F(2, 20) = 5.3061$, $p < 0.05$), device and channel group ($F(2, 20) = 16.3133$, $p < 0.001$), condition and channel group ($F(1, 10) = 8.9950$, $p < 0.05$), as well as device, condition, and channel group ($F(2, 20) = 9.6415$, $p < 0.05$).

The post-hoc analysis revealed that when participants had their eyes closed, delta power was significantly reduced compared to the eyes open conditions ($t=-11.853$, $p<0.001$). Additionally, delta power was stronger over the posterior group of channels compared to the anterior group ($t=5.9207$, $p<0.001$). In the eyes open condition, recordings from Neiry Headband exhibited higher delta power compared to the NVX recordings ($t=2.811$, $p<0.05$) and Muse recordings ($t=4.602$, $p<0.001$). Moreover, NVX recordings had higher delta power than Muse recordings ($t=3.350$, $p<0.05$). Conversely, during the eyes closed condition, delta power was stronger in the recordings from Neiry Headband compared to NVX recordings ($t=4.345$, $p<0.001$). However, NVX recordings had lower delta power than Muse recordings ($t=-2.407$, $p<0.05$). Notably, delta power substantially increased after the eyes opened for both the Neiry Headband recordings ($t=12.339$, $p<0.001$) and NVX recordings ($t=17.397$, $p<0.001$).

The delta power was significantly different across the devices and sites. Specifically, the Neiry Headband recordings consistently yielded higher delta power compared to NVX recordings over both the posterior ($t=2.915$, $p<0.05$) and anterior sites ($t=4.252$, $p<0.001$). In comparison to Muse, Neiry Headband recordings had higher delta power only for the anterior sites ($t=4.158$, $p<0.001$). Notably, there was a significant decrease

in delta power over the anterior sites compared to posterior sites, but this pattern was observed only for the NVX (t=-10.932, p<0.001) and Muse recordings (t=-6.717, p<0.001).

For the eyes-open condition considered separately, delta power over the anterior sites was stronger for the Neiry Headband recordings as compared to Muse (t=5.049, p<0.001), and in the NVX recordings as compared to Muse (t=3.950, p<0.05). For the eyes-closed condition, delta power was stronger for the Neiry Headband than for NVX for both the anterior (t=3.582, p<0.05) and posterior (t=2.511, p<0.05) sites. Furthermore, a statistically significant positive difference in delta power between the eyes-open and eyes-closed conditions was found for the Neiry recordings over the posterior (t=8.828, p<0.001) and anterior sites (t=8.454, p<0.001), for NVX over the posterior sites (t=11.368, p<0.001) and anterior sites (t=13.206, p<0.001), and for Muse only over the posterior sites (t=4.484, p<0.05).

The ANOVA analysis conducted for the theta band data (Fig. 3, B) revealed that there was no significant main effect of the recording device ($F(2,20) = 0.6968$, $p = 0.5099$). However, both condition ($F(1,10) = 16.2164$, $p < 0.05$) and channel group ($F(1,10) = 99.6514$, $p < 0.001$) had significant main effects. Interactions between device and condition ($F(2,20) = 2.9222$, $p = 0.0770$) and condition and channel ($F(1,10) = 0.1589$, $p = 0.6986$) were found to be non-significant. On the other hand, the interactions between device and channel ($F(2,20) = 12.9638$, $p < 0.001$) and device, condition, and channel ($F(2,20) = 10.0947$, $p < 0.001$) were statistically significant.

When participants had their eyes closed, theta power was significantly suppressed ($t = -8.5827$, $p < 0.001$). Furthermore, theta power was more prominent over the posterior sites compared to the anterior sites ($t = 9.4043$, $p < 0.001$).

The theta power exhibited distinct patterns across the different recording devices. Specifically, in the Neiry Headband recordings, theta power was lower compared to Muse recordings over the posterior sites ($t = -2.77$, $p < 0.05$), while it was larger at the anterior sites ($t = 2.875$, $p < 0.05$). On the other hand, in NVX recordings, theta power was suppressed over the posterior sites compared to Muse ($t = -3.656$, $p < 0.05$) and over the anterior sites compared to Neiry Headband ($t = -3.718$, $p < 0.05$). Furthermore, a general tendency for the theta power being lower at the anterior sites compared to the posterior ones was observed for both NVX ($t = -10.471$, $p < 0.001$) and Muse recordings ($t = -8.9333$, $p < 0.001$).

The theta power had significant differences across the recording devices and eye conditions. When the eyes were open, Neiry Headband's theta power was significantly higher compared to Muse for the anterior regions (t=3.495, p<0.05). Conversely, the NVX's theta power was significantly lower compared to Muse for the posterior regions when the eyes were closed (t=-3.17, p<0.05). Additionally, the theta power in the Neiry Headband recordings was significantly higher than in the NVX recordings for the anterior regions when the eyes were closed (t=3.387, p<0.05).

Furthermore, when the eyes were open, the theta power over the posterior regions increased for the Neiry Headband (t=5.535, p<0.001), NVX (t=5.785, p<0.001) and

Muse ($t=3.633$, $p<0.05$). Over the anterior channels, this increase was observed only for the Neiry Headband ($t=6.313$, $p<0.001$) and NVX ($t=8.033$, $p<0.001$).

The ANOVA conducted for the alpha frequency range (Fig. 3, C) yielded significant main effects of the recording device ($F(2,20)=3.9126$, $p<0.05$) and channel group ($F(1,10)=155.2894$, $p<0.001$). However, the main effect of condition did not reach significance ($F(1,10)=1.8573$, $p=0.2028$). The interactions between device and condition ($F(2,20)=1.1401$, $p=0.3397$) and device and channel ($F(2,20)=2.2727$, $p=0.1290$) were also non-significant. In contrast, the interactions between condition and channel group were significant ($F(1,10)=18.1444$, $p<0.05$), as well as the interactions between device, condition, and channel group ($F(2,20)=9.3815$, $p<0.05$).

For the posterior regions, the alpha power was significantly stronger when the eyes were closed compared to when they were open ($t=-4.295$, $p<0.001$). This effect was statistically significant for the Neiry Headband ($t=-3.199$, $p<0.05$) and NVX ($t=-4.739$, $p<0.001$) recordings. Additionally, when the eyes were closed, the Neiry Headband recordings had higher alpha power for the posterior channels than the recordings with Muse ($t=5.366$, $p<0.001$), and NVX had higher alpha power for the posterior channels compared to Muse ($t=4.855$, $p<0.001$).

The ANOVA analysis conducted for the low beta frequency range (Fig. 3, D) showed a significant main effect of the channel group ($F(1,10) = 85.0479$, $p < 0.001$). The main effects of the recording device ($F(2,20) = 0.3708$, $p = 0.6949$) and experimental condition ($F(1,10) = 0.4008$, $p = 0.5409$) were not statistically significant. The interaction between device and condition ($F(2,20) = 0.0467$, $p = 0.9544$) and the interaction between device, condition, and channel group ($F(2,20) = 2.3409$, $p = 0.1220$) were not significant either. The only significant interactions were found between device and channel ($F(2,20) = 4.7482$, $p < 0.05$) and between condition and channel ($F(1,10) = 15.2382$, $p < 0.05$).

The low-beta power was stronger for the posterior than anterior channels ($t = 16.0988$, $p < 0.001$). Additionally, NVX recordings exhibited stronger low-beta power for the posterior channels as compared to both Neiry Headband ($t = 4.9032$, $p < 0.001$) and Muse ($t = 2.353$, $p < 0.05$).

Similar to the findings for the low beta power, the ANOVA analysis conducted on beta power (Fig. 3, E) also revealed a significant main effect of the channel group ($F(1,10) = 57.9745$, $p < 0.001$). However, the main effects of the recording device ($F(2,20) = 1.5483$, $p = 0.2370$) and experimental condition ($F(1,10) = 1.2502$, $p = 0.2897$) did not reach statistical significance. Likewise, the interactions between device and condition ($F(2,20) = 0.2764$, $p = 0.7613$) and between device, condition, and channel group ($F(2,20) = 2.2954$, $p = 0.1266$) were not significant. The only noteworthy interactions were observed between device and channel ($F(2,20) = 4.6081$, $p < 0.05$) and between condition and channel ($F(1,10) = 15.6154$, $p < 0.05$).

The beta power was notably higher for the posterior channels compared to the anterior channels ($t = 13.142$, $p < 0.001$). For the anterior channels, the beta power was more stronger during the eyes-open condition compared to the eyes-closed condition

($t = 3.272$, $p < 0.05$). Moreover, NVX recordings displayed greater beta power for the posterior channels compared to both Neiry Headband ($t = 6.919$, $p < 0.001$) and Muse ($t = 3.243$, $p < 0.05$).

The results from the ANOVA analysis for high beta power (Fig. 3, F) yielded several distinct findings. The main effects of the recording device ($F(2,20) = 5.5221$, $p < 0.05$), experimental condition ($F(1,10) = 8.1142$, $p < 0.05$), and channel group ($F(1,10) = 22.1371$, $p < 0.001$) were all found to be significant. However, the interactions between device and condition ($F(2,20) = 1.6315$, $p = 0.2206$) and between device, condition, and channel group ($F(2,20) = 1.1531$, $p = 0.3358$) were not significant. Additionally, the interactions between device and channel group ($F(2,20) = 4.9652$, $p < 0.05$) and between condition and channel group ($F(1,10) = 18.0802$, $p < 0.05$) were significant.

During the eyes-closed condition, high-beta power was significantly suppressed compared to the eyes-open condition ($p = -5.6774$, $p < 0.001$). Conversely, for comparison of the eyes-open condition versus eyes-closed condition, high-beta power was higher over the anterior sites ($t = 5.903$, $p < 0.001$). Moreover, high-beta power was higher over the posterior than anterior channels ($p = 7.7817$, $p < 0.001$).

In terms of the recording devices, the NVX recordings had a higher high-beta power compared to Muse recordings ($t = 2.4525$, $p < 0.05$) and Neiry Headband recordings ($t = 6.1265$, $p < 0.001$). Additionally, the Muse recordings had a elevated high-beta power compared to the Neiry Headband recordings ($t = 3.137$, $p < 0.001$).

Considering the posterior channels specifically, the high beta power was suppressed for the Neiry Headband recordings compared to NVX ($t = -8.956$, $p < 0.001$) and Muse ($t = -3.795$, $p < 0.001$) while it was elevated for the NVX compared to Muse ($t = 4.036$, $p < 0.001$).

The ANOVA analysis conducted for the gamma frequency range (Fig. 3, G) revealed significant main effects for device ($F(2,20) = 7.4974$, $p < 0.05$), condition ($F(1,10) = 10.4112$, $p < 0.05$), and channel group ($F(1,10) = 16.4423$, $p < 0.05$). However, the interactions between device and condition ($F(2,20) = 2.6102$, $p = 0.0984$) and between device, condition, and channel group ($F(2,20) = 1.5608$, $p = 0.2345$) were not statistically significant. In contrast, the interactions between device and channel ($F(2,20) = 4.0474$, $p < 0.05$) as well as between condition and channel ($F(1,10) = 11.7374$, $p < 0.05$) were significant.

Similar to the the findings for high beta, the gamma power was lower during eyes closed than eyes open ($t = -6.5174$, $p < 0.001$). This effect was strongest for the posterior channels ($t = 6.7493$, $p < 0.001$). Yet, this effect was significant only for NVX ($t = 6.426$, $p < 0.001$) and Muse ($t = 3.906$, $p < 0.001$).

Comparing the recording devices, the gamma power recorded by Muse was lower compared to the NVX recordings ($t = -3.7136$, $p < 0.05$) recordngs and higher compared to Neiry Headband recordings ($t = 3.2283$, $p < 0.05$). Additionally, gamma power was lower for Neiry Headband as compared to NVX ($t = -6.9752$, $p < 0.001$).

Considering the signal spatial properties, the posterior channels of Neiry Headband had lower gamma power compared to both NVX ($t = -9.310$, $p < 0.001$) and Muse (t

= -3.913, p $<$ 0.001). Conversely, the posterior channels of NVX had higher gamma power compared to Muse (t = 4.595, p $<$ 0.001).

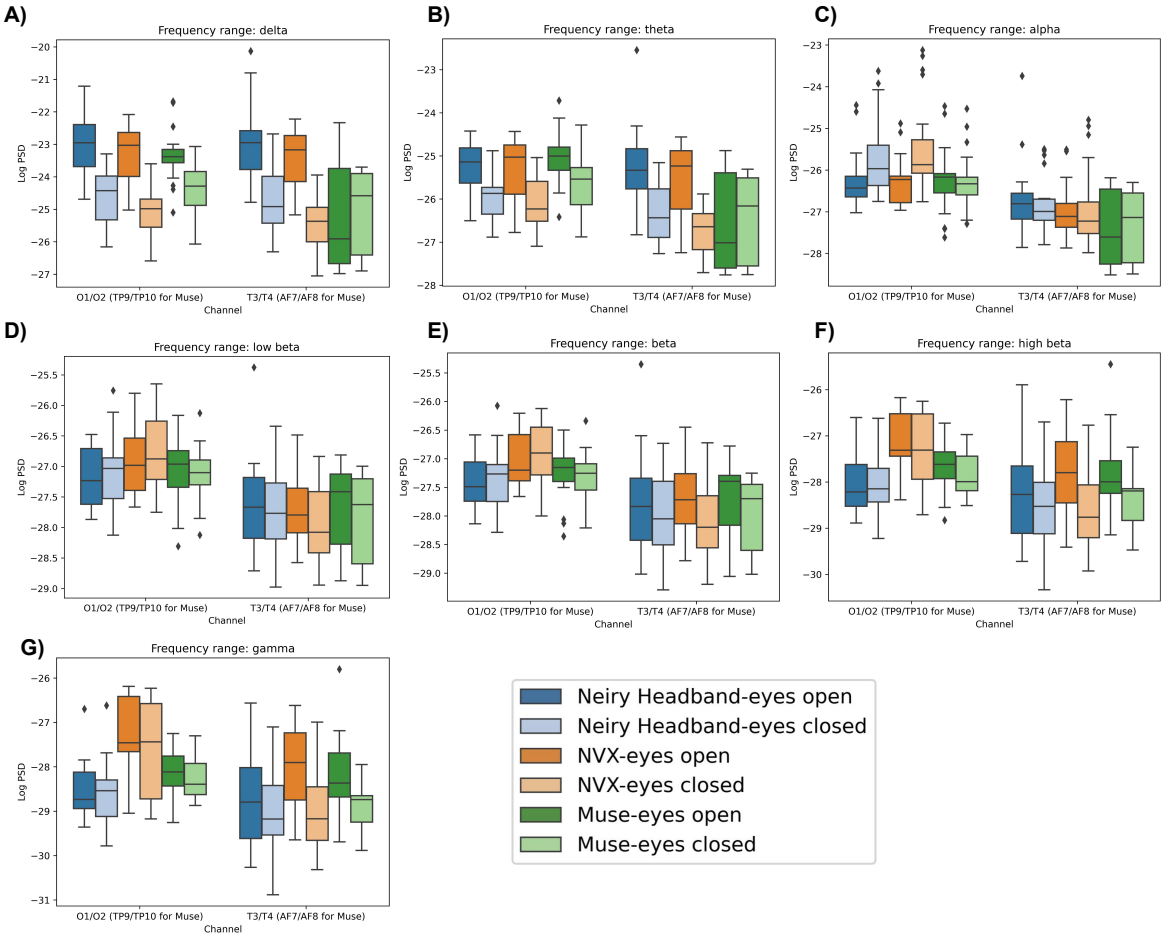

Figure 3: Boxplots showing the distribution of mean log PSD values across conditions and channel groups for different frequency ranges: delta (A), theta (B), alpha(C), low beta (D), beta (E), high beta (F), gamma (G)

3.3. Correlation analysis

The correlation analysis of mean log PSD values revealed that across all frequency ranges, EEG signals of the Neiry Headband matched the conventional EEG recordings obtained with NVX better than those obtained with Muse. Additionally, the correlations between the NVX and Muse were weaker than the correlations observed between the Neiry Headband and NVX. (Fig. 4).

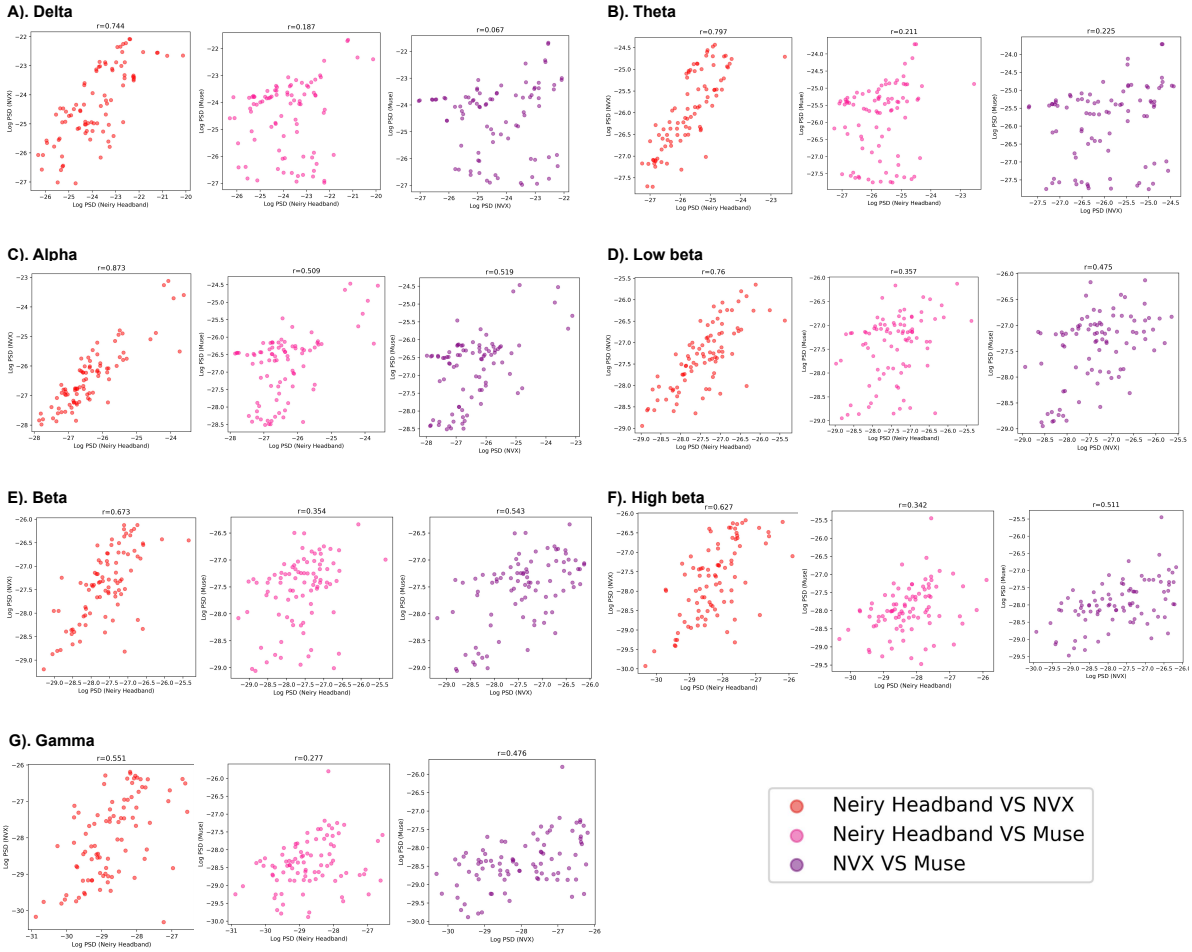

Figure 4: The correspondence between the recordings obtained with different devices assessed as pairwise correlations of mean log PSD values for different frequency ranges

As it is clear from Table 1, most of the correlation values were found to be statistically significant with the exception for two values for the delta frequency band: the correlation between Neiry Headband and Muse ($r(86)=0.187$, $p=0.081$), and the correlation between NVX and Muse ($r(86)=0.067$, $p=0.535$). For all other frequency ranges, the correlations were significant. The correlation was the highes for the comparison of the alpha-range signals of the Neiry Headband and NVX ($r(86)=0.873$, $p<0.001$).

Frequency range/Devices	Neiry Headband VS NVX	Neiry Headband VS Muse	NVX VS Muse
Delta	r(86)=0.744, p<0.001	r(86)=0.187, p=0.081	r(86)=0.067, p=0.535
Theta	r(86)=0.797, p<0.001	r(86)=0.211, p<0.05	r(86)=0.225, p<0.05
Alpha	r(86)=0.873, p<0.001	r(86)=0.509, p<0.001	r(86)=0.519, p<0.001
Low beta	r(86)=0.76, p<0.001	r(86)=0.357, p<0.001	r(86)=0.475, p<0.001
Beta	r(86)=0.673, p<0.001	r(86)=0.354, p<0.001	r(86)=0.543, p<0.001
High beta	r(86)=0.627, p<0.001	r(86)=0.342, p<0.05	r(86)=0.511, p<0.001
Gamma	r(86)=0.551, p<0.001	r(86)=0.277, p<0.05	r(86)=0.476, p<0.001

Table 1: Results of correlation analysis

4. Discussion

In the present study, we obtained resting-state EEG data using several recording devices. Although unsophisticated, monitoring resting-state cortical activity has multiple medical and consumer applications, so perfecting these kind of recordings and making them affordable and easy to implement offers multiple benefits. Yet, the potential users of EEG equipment would also benefit from a realistic assessment of the performance of these systems. Here we compared the recordings obtained with two consumer-grade EEG devices, the Neiry Headband and the Muse Headband, with the data collected with the medical-grade device, the NVX. We found distinct sets of signal-quality parameters that could be applied to the comparison of different recording devices, illuminating their potential advantages and limitations for various EEG-based applications.

The performance in the delta-rhythm band is of great interest because of the applications where awake and sleep (not considered here) states could be assessed. Here, the Neiry Headband consistently had a higher delta power than the other devices. This was particularly clear for the eyes open condition, and for the T3/T4 channels of Neiry. By contrast, the AF7/AF8 of Muse had an attenuated delta power. While this finding suggests that the Neiry Headband is suitable for the monitoring of low-frequency EEG components (Hinrichs et al., 2020), this frequency range is also prone to low-frequency artifacts which are difficult to control in consumer settings. Yet, we should not dismiss the low-frequency signal as merely noisy particularly because the Neiry Headset was capable of detecting an increase in delta power (as well as theta power) during eyes-open conditions, which aligns with the idea of unstructured processing of the environment (Barry et al., 2007). The same effect was seen in the NVX recordings, which supports the validity of the Neiry Headband's findings. Accordingly, our tests lend credibility to the Neiry Headband's data in the low-frequency range. The Muse recordings detected this modulation only at the posterior channels, which questions the reliability of delta-rhythm monitoring recordings with this device.

For the theta-frequency range, our results showed that the Neiry Headband exhibited suppressed theta power compared to Muse for the posterior channels, while it yielded higher theta power than Muse for the anterior channels. The NVX system also

exhibited unique patterns. In particular, its posterior theta power was lower compared to Muse and its anterior theta power was higher compared to Neiry. These spatial difference could become important for the applications based on the comparison of theta power in different cortical regions. Notably the Neiry Headband and NVX successfully detected increased theta power when the eyes were closed, which could be considered a standard spectral change (Barry et al., 2007).

The alpha frequency range, is perhaps the most reliable feature of these kind of recordings because alpha oscillations are typically very prominent and could be easily distinguished from the artifacts. In this range the Muse device was less sensitive compared to the NVX and Neiry Headband recordings, which, combined with the consideration of the Muse reduced spatial coverage, suggests this device does not effectively capture alpha activity, particularly over the posterior brain regions. By contrast, the posterior-alpha rhythm was reliably detected by the Neiry Headband and NVX. In particular, these devices detected posterior alpha suppression when the eyes were open (Barry et al., 2007). When the eyes were closed and posterior alpha activity was highly synchronized, the Neiry Headband and the NVX system signals were stronger compared to the Muse Headband. As to the low-beta, beta, and high-beta and gamma activity over the posterior regions, the NVX was consistently more sensitive compared to both Neiry Headband and Muse recordings.

The correlation analysis revealed that the Neiry Headband matched the NVX readings better than Muse across all frequency ranges. We conclude that Neiry's dry-electrode technology shows an overall consistency with the standard medical-grade measurements. We suggest that such correlation analysis is conducted for consumer EEG systems as a key benchmark of performance.

Overall, our results suggest that dry-electrode systems, such as the Neiry Headband, are appropriate for such consumer application as cognitive monitoring where delta, theta and alpha frequency readings are used to assess the cognitive state. Yet, when selecting the system to use, it is essential to consider the specific research objectives and frequency bands of interest. Thus, for tasks that involve high-frequency oscillations (beta and gamma), the gel electrode-based NVX system is still a more suitable choice due to its higher power sensitivity in these frequency ranges. One limitation of the study is the specific electrode configurations used for each device. Different electrode placements and spatial coverage could have contributed to the observed differences in signal quality.

In conclusion, our findings highlight the distinct characteristics of signal quality across different recording devices and frequency ranges. The results suggest that the choice of device significantly influences the measurements of EEG power in different frequency bands and brain regions. Researchers and practitioners should carefully consider the specific application and frequency ranges of interest when selecting and recommending an appropriate recording device. The modern dry electrode technology showed promising results, but its performance should be additionally evaluated based on the specific research context and experimental modulation of such cognitive states as relaxation, stress, mental workload, and the others.

Overall, this study contributes to the growing body of research on the dry electrode technology, its potential applications in EEG research and real-world EEG-based applications, and the development of unified requirements for consumer-grade applications of this type.

References

Arsalan, A., Majid, M., Butt, A. R., and Anwar, S. M. (2019). Classification of perceived mental stress using a commercially available eeg headband. *IEEE journal of biomedical and health informatics*, 23(6):2257–2264.

Asif, A., Majid, M., and Anwar, S. M. (2019). Human stress classification using eeg signals in response to music tracks. *Computers in biology and medicine*, 107:182–196.

Bajada, J. and Bonello, F. B. (2021). Real-time eeg-based emotion recognition using discrete wavelet transforms on full and reduced channel signals. *arXiv preprint arXiv:2110.05635*.

Bano, K. S., Bhuyan, P., and Ray, A. (2022). Eeg-based brain computer interface for emotion recognition. In *2022 5th International Conference on Computational Intelligence and Networks (CINE)*, pages 1–6. IEEE.

Barry, R. J., Clarke, A. R., Johnstone, S. J., Magee, C. A., and Rushby, J. A. (2007). Eeg differences between eyes-closed and eyes-open resting conditions. *Clinical neurophysiology*, 118(12):2765–2773.

Bitner, R. and Le, N.-T. (2022). Can eeg-devices differentiate attention values between incorrect and correct solutions for problem-solving tasks? *Journal of Information and Telecommunication*, 6(2):121–140.

Cannard, C., Wahbeh, H., and Delorme, A. (2021). Validating the wearable muse headset for eeg spectral analysis and frontal alpha asymmetry. In *2021 IEEE International Conference on Bioinformatics and Biomedicine (BIBM)*, pages 3603–3610. IEEE.

Gramfort, A., Luessi, M., Larson, E., Engemann, D. A., Strohmeier, D., Brodbeck, C., Goj, R., Jas, M., Brooks, T., Parkkonen, L., et al. (2013). Meg and eeg data analysis with mne-python. *Frontiers in neuroscience*, page 267.

Hinrichs, H., Scholz, M., Baum, A. K., Kam, J. W., Knight, R. T., and Heinze, H.-J. (2020). Comparison between a wireless dry electrode eeg system with a conventional wired wet electrode eeg system for clinical applications. *Scientific reports*, 10(1):5218.

Kam, J. W., Griffin, S., Shen, A., Patel, S., Hinrichs, H., Heinze, H.-J., Deouell, L. Y., and Knight, R. T. (2019). Systematic comparison between a wireless eeg system with dry electrodes and a wired eeg system with wet electrodes. *NeuroImage*, 184:119–129.

Katahira, K., Yamazaki, Y., Yamaoka, C., Ozaki, H., Nakagawa, S., and Nagata, N. (2018). Eeg correlates of the flow state: A combination of increased frontal theta and moderate frontocentral alpha rhythm in the mental arithmetic task. *Frontiers in psychology*, 9:300.

Krigolson, O. E., Williams, C. C., Norton, A., Hassall, C. D., and Colino, F. L. (2017). Choosing muse: Validation of a low-cost, portable eeg system for erp research. *Frontiers in neuroscience*, 11:109.

Marini, F., Lee, C., Wagner, J., Makeig, S., and Gola, M. (2019). A comparative evaluation of signal quality between a research-grade and a wireless dry-electrode mobile eeg system. *Journal of neural engineering*, 16(5):054001.

Myrden, A. and Chau, T. (2017). A passive eeg-bci for single-trial detection of changes in mental state. *IEEE Transactions on neural systems and rehabilitation Engineering*, 25(4):345–356.

Niso, G., Romero, E., Moreau, J. T., Araujo, A., and Krol, L. R. (2023). Wireless eeg: A survey of systems and studies. *NeuroImage*, 269:119774.

Papakostas, M., Tsiakas, K., Giannakopoulos, T., and Makedon, F. (2017). Towards predicting task performance from eeg signals. In *2017 IEEE International Conference on Big Data (Big Data)*, pages 4423–4425. IEEE.

Przegalinska, A., Ciechanowski, L., Magnuski, M., and Gloor, P. (2018). Muse headband: Measuring tool or a collaborative gadget? *Collaborative Innovation Networks: Building Adaptive and Resilient Organizations*, pages 93–101.

Radüntz, T. (2018). Signal quality evaluation of emerging eeg devices. *Frontiers in physiology*, 9:98.

Ratti, E., Waninger, S., Berka, C., Ruffini, G., and Verma, A. (2017). Comparison of medical and consumer wireless eeg systems for use in clinical trials. *Frontiers in human neuroscience*, 11:398.

Sun, J. C.-Y. and Yeh, K. P.-C. (2017). The effects of attention monitoring with eeg biofeedback on university students' attention and self-efficacy: The case of anti-phishing instructional materials. *Computers & Education*, 106:73–82.

Trejo, L. J., Kubitz, K., Rosipal, R., Kochavi, R. L., Montgomery, L. D., et al. (2015). Eeg-based estimation and classification of mental fatigue. *Psychology*, 6(05):572.

Welch, P. (1967). The use of fast fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. *IEEE Transactions on audio and electroacoustics*, 15(2):70–73.

Wyckoff, S. N., Sherlin, L. H., Ford, N. L., and Dalke, D. (2015). Validation of a wireless dry electrode system for electroencephalography. *Journal of neuroengineering and rehabilitation*, 12(1):1–9.