# Real-Time Brain Health Monitoring During Blast Overpressure Using EEG Integrated Hearing Protection

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## Abstract

**Background:** Blast overpressure exposure during military breaching operations poses a significant risk for mild traumatic brain injury (mTBI). Current safety protocols rely heavily on “minimum safe distance” (MSD) and subjective symptom reporting, often failing to capture immediate physiological effects. A major gap exists in the ability to monitor cognitive health in real-time during exposure events.

**Methods:** This study utilized the Ops-Core AMP Neuro headset, a novel EEG-integrated hearing protection system, to collect longitudinal brain health data from military and law enforcement personnel during a multi-day breaching training program. Data collection included resting-state "cognitive snapshots" (eyes-open/eyes-closed) before and after exercises, as well as passive background monitoring during live fire events.

**Results:** Analysis of the resting-state power band metrics revealed **increased Theta power, increased Delta power, and reduced Alpha power** across the cohort over the course of the training week. In at least one user, real-time spectral analysis identified a distinct "ramp up" of Theta activity occurring approximately 10 minutes following blast exposure. Furthermore, increased slow-wave activity and decreased fast-wave activity showed significant correlations with behavioral reports of mTBI symptoms.

**Conclusion:** This study presents the first-ever neural dataset collected during live blast overpressure exposure. The findings provide evidence that wearable, EEG-integrated hearing protection can successfully identify objective biomarkers of mTBI in operational environments, offering a viable pathway for real-time brain health monitoring.

# Background

## The Challenge of Blast Overpressure

Military personnel involved in breaching operations are routinely exposed to blast overpressure - shock waves generated by explosive charges (Figure 1). While the immediate physical effects of high-level blasts are well-documented, the cumulative neurological impact of repeated, low-level exposure remains a critical area of concern. Current safety protocols largely rely on minimum safe distances (MSDs) and subjective symptom reporting. However, subjective self-reports can be unreliable due to adrenaline, confusion, or a lack of immediate symptom awareness.

Figure 1: Example of blast overpressure experienced by military personnel involved in breaching operations

## The Gap in Real-Time Assessment

A significant limitation in understanding blast-induced mild traumatic brain injury (mTBI) is the lack of objective physiological data collected during the exposure event itself. Traditional neuroimaging and cognitive assessments are typically administered hours or days post-injury. This delay creates a "black box" regarding the immediate neural response to blast waves. Past literature indicates that the first 10 to 60 minutes after a mild TBI are critical, often characterized by specific spectral changes such as increased Delta and Theta power and reduced Alpha power[1]. Yet, without real-time monitoring, these transient but diagnostic biomarkers are often missed.

## Study Objectives

To address this gap, Neurable developed a novel form of EEG-integrated hearing protection. This form factor allows for the continuous collection of high-fidelity neural data in operational environments without interfering with standard safety equipment.

The primary objectives of this study were to:

1. Establish a baseline of cognitive function prior to breaching operations.
2. Monitor longitudinal changes in resting-state EEG metrics (Delta, Theta, Alpha) throughout a multi-day breaching training program.
3. Demonstrate the feasibility of collecting passive EEG data during live breaching exercises.

By capturing data before, during, and after exposure, this study aims to present the first-ever neural dataset of its kind, offering new insights into the real-time physiological burden of blast overpressure[2].

# Methods

## EEG-Integrated Hearing Protection

Neural data was acquired using **Neurable's AMP Neuro headset** (Figure 2). AMP Neuro was developed by integrating Neurable's proprietary dry EEG acquisition and signal processing technology into Gentex's Ops Core hearing protection headset. The system retains all of Ops Core's original capability and functions as EEG-integrated hearing protection, allowing for the collection of high-fidelity brain health data in operational environments without compromising auditory safety. The headset was configured to record passive EEG data during both resting states and active breaching exercises. The data included 12 dry EEG channels (6 around each ear) recorded locally at 500 Hz and via Bluetooth streaming at 125 Hz.

Figure 2: Neurable's AMP Neuro Hearing Protection Headset

## Subjects

A total of 6 participants volunteered for data collection in this observational study. Three of the participants (User 01-03) were instructors who were routinely exposed to blast overpressure, whereas the

other three participants (User 04-06) were trainees with limited exposure to blast overpressure prior to the program. All subjects participated in breaching operations as part of their existing training activities. The research was strictly observational in that no blast exposures were added specifically for the study.

Figure 3: Operators wearing Neurable AMP Neuro headsets positioned at a minimum safe standoff distance ahead of breaching blast exposure.

## Study Protocol

On the first day of the experiment, participants completed an intake questionnaire to provide background information regarding their age, handedness, blast overpressure history, and current cognitive state. Following the intake questionnaire, each participant completed a 'cognitive snapshot' session while wearing the AMP Neuro headset. During each cognitive snapshot, participants were instructed to sit still while looking straight ahead with their eyes open for 20 seconds followed by eyes closed for 20 seconds, all for a total of 3 rounds. Each session lasted approximately 2 minutes with the eyes-open and eyes-closed intervals guided by audio cues played through an external speaker. This provides the baseline cognitive data before any participants were potentially exposed to blast overpressure as a result of their breaching operations.

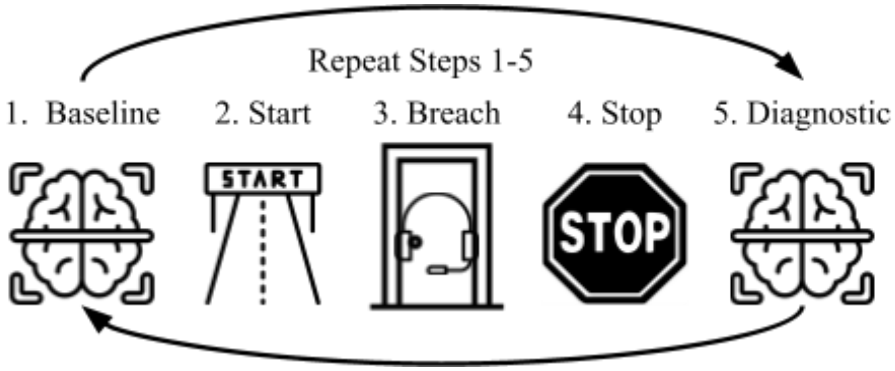


Figure 4: Study protocol used to collect EEG data from participants before, during and after exposure to blast overpressure

During the subsequent days, participants completed a cognitive ratings questionnaire, a shortened version of the intake questionnaire focused primarily on the subjective ratings of their current cognitive state, along with a cognitive snapshot session before and after each breaching exercise. Additionally, the participants closest to blast (with the shortest minimal safety distance (MSD)) were instructed to wear the AMP Neuro headset to collect passive EEG data in the background as they performed live breaching exercises. Together, EEG data were collected from participants before, during and after potential blast overpressure exposure, representing the first ever neural dataset of its kind to be collected (Figure 4).

### Control Protocol

Three participants with no prior exposure to blast overpressure or known brain injury served as the control group. They took the same cognitive snapshot as the blast participants while seated in an office, using the MW75 Neuro headset for three days. They took nine cognitive snapshots between 9 am and 6 pm to capture circadian rhythms. Between day two and day three, participants were instructed to sleep at least 2 hours less than their typical amount to induce EEG patterns similar to those observed in mTBI.

### Data Analysis

EEG data were processed to extract resting-state power-band metrics using 5 Hz to 100 Hz bandpass filters and a 60 Hz notch filter. Spectral power was analyzed across the following frequency bands: Delta, Theta, Alpha, Beta (Low/High), Gamma, and Alpha Peak Frequency. The resulting metrics were transformed into standardized distributions relative to the population averages, according to Neurable's past research, so values of 100 represented population averages, and values below 75 or above 125 were considered one standard deviation from population averages, and values below 42 or above 157 were considered two standard deviations from population averages. Population averages were determined from the TD Brains open-source dataset[4].

To identify relationships between neural changes and subjective symptoms, quantitative EEG (qEEG) variables from the pre-blast and post-blast cognitive snapshots were correlated with behavioral variables (e.g., "How cognitively sharp do you feel?", "Hearing difficulty"). Statistical significance was assessed calculating Pearson correlations, with significance thresholds set at $p < 0.05$. These correlations were assessed within individual participants.

The EEG data during the training sessions (during blast training) was collected from participants who were standing and freely moving. To control for motion artifacts, Neurable's proprietary Novel Motion Artifact Rejection (NMAR) algorithm was used in preprocessing before spectral power extraction.

## Results

### Pre vs. Post Blast EEG Comparisons

Analysis of resting-state power band metrics collected before and after blast training sessions revealed distinct longitudinal trends across the cohort. Consistent with the hypothesis of blast-induced neural strain, the most significant observation was an **increased Theta power** over the course of the week across all participants. Additionally, most participants exhibited **increased Delta power** and **decreased Alpha**

**power** following exposure (Figure 5). Values approached or exceeded two standard deviations from the population mean.

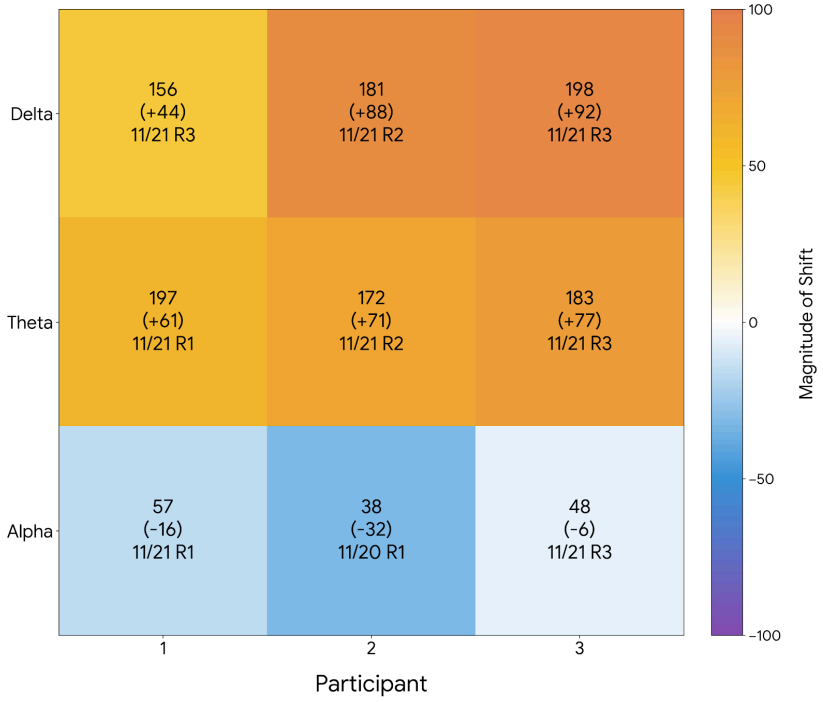


Figure 5: Heatmap displaying the greatest change in power band measurement from baseline session. The top value of the cell is the recorded measurement; the middle value is the change from baseline; and the bottom value is the date and round of blasts from which the measurement is taken.

Specific user data highlights these trends:

**User 01 (Theta & Delta Increase):** This subject began with the highest baseline values, potentially indicative of their substantial history of blast overpressure exposure, and showed increases throughout the week. From a baseline of **123** on Day 1, Theta power gradually increased throughout the sessions, reaching **197** after the first breaching exercise on Day 2 and ending at **171** after the final breaching exercise.

**User 02 (Theta & Delta Increase):** This subject showed pronounced shifts across Theta and Delta. Baseline Theta power on Day 1 was 101, then reached a maximum of **172** on Day 3. Similarly, Delta power rose from a baseline of **93** on Day 1 to a peak of **181** on Day 3.

**User 03 (Delta/Theta Variability):** While less linear than other subjects, User 03 exhibited a late-week surge in low-frequency activity, with Delta power reaching **198** and Theta power peaking at **183** after the final round of breaching on Day 3.

**Users 04 - 06:** These trainees were positioned at greater distance from the breach charges and recorded fewer EEG sessions, so less data is available. Nevertheless, all these trainees exhibited at least slightly elevated Theta power after breaching relative to the first recordings of the week.

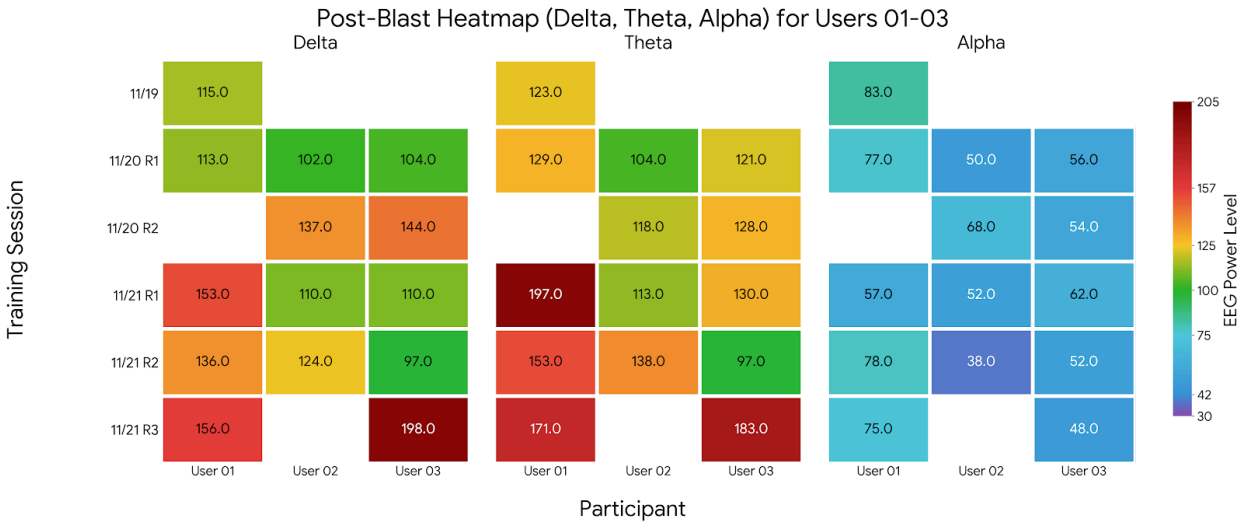


Figure 6. Heatmap displaying the post-blast power band measurement for Delta, Theta, and Alpha. Delta and Theta are generally higher (> 125) than typical values (green), while Alpha is lower than typical (< 75).

## Correlations: qEEG Metrics vs. Behavioral Reports

We compared quantitative EEG (qEEG) features with subjective behavioral reports (e.g., "How cognitively sharp do you feel?", "Feeling dizzy", "Vision problems, blurring, trouble seeing") to identify potential neural markers of mTBI symptoms (Table 1). Correlations were evaluated within each participant to avoid false positives due to between-subject variability. The dataset included 27 time points across three participants; however, User 02 (N=8) reported minimal symptom variability and showed no significant correlations. For User 01 (N=9) and User 03 (N=10), the following trends were observed:

1. **Sensory Disruption:**
    - **Vision Problems:** Reported vision problems or blurring were associated with decreased High Beta activity for User 01 ($r = -0.70$, $p < 0.05$) and increased Alpha Peak Frequency for User 03 ($r = 0.67$, $p < 0.05$).
    - **Combined Sensory Subscale:** When vision and hearing difficulty items were combined into a sensory symptom subscale, the resulting score correlated with decreased High Beta activity for User 01 ($r = -0.74$, $p < 0.05$).
2. **Physical Symptoms**
    - **Dizziness:** For User 01, reports of feeling dizzy were associated with increased Delta ($r = 0.75$, $p < 0.05$) and Theta activity ($r = 0.77$, $p < 0.05$), along with decreased Alpha ($r = -0.75$, $p < 0.05$) and Low Beta activity ($r = -0.89$, $p < 0.01$). For User 03, dizziness was associated with increased Alpha Peak Frequency ($r = 0.63$, $p < 0.05$).
    - **Combined Physical Subscale:** When dizziness and headache items were combined into a physical symptom subscale, the resulting score correlated with increased Delta ($r = 0.77$, $p < 0.05$) and Theta activity ($r = 0.76$, $p < 0.05$), and decreased Alpha ($r = -0.68$, $p < 0.05$) and Low Beta activity ($r = -0.91$, $p < 0.01$) for User 01. For User 03, the physical subscale correlated with increased Alpha Peak Frequency ($r = 0.63$, $p < 0.05$).
3. **Cognitive Symptoms:**

- **Disorientation (mental confusion):** For User 01, self-reported disorientation was associated with increased Delta ($r = 0.79$, $p < 0.05$) and Theta activity ($r = 0.76$, $p < 0.05$), along with decreased Low Beta activity ($r = -0.81$, $p < 0.01$). For User 03, disorientation correlated with increased Theta activity ($r = 0.67$, $p < 0.05$) and decreased Gamma activity ($r = -0.78$, $p < 0.01$).
- **Trouble Concentrating:** For User 01, trouble concentrating was associated with increased Delta ($r = 0.81$, $p < 0.01$) and Theta activity ($r = 0.68$, $p < 0.05$), and decreased Low Beta activity ($r = -0.81$, $p < 0.01$). For User 03, trouble concentrating correlated with decreased Gamma activity ($r = -0.67$, $p < 0.05$).
- **Combined Cognitive Subscale:** When combined into a cognitive subscale of mTBI symptoms, the resulting score correlated with increased Delta ($r = 0.84$, $p < 0.01$) and Theta activity ($r = 0.72$, $p < 0.05$), and decreased Low Beta activity ($r = -0.91$, $p < 0.01$) for User 01. For User 03, the cognitive subscale correlated with decreased Gamma activity ($r = -0.77$, $p < 0.01$).

4. **Combined Scale:**
   - When all self-report items were combined into a single score, the resulting score correlated with increased Delta ($r = 0.83$, $p < 0.01$) and Theta activity ($r = 0.75$, $p < 0.05$), and decreased Low Beta activity ($r = -0.92$, $p < 0.01$) for User 01. For User 03, the combined symptom score correlated with decreased Gamma activity ($r = -0.80$, $p < 0.01$).

Table 1: qEEG Metrics vs. Behavioral Symptom Correlations

| Symptom Category | Behavioral Report / Subscale | User | qEEG Metric | Correlation (r) | Significance (p) |
|---|---|---|---|---|---|
| Sensory | Vision Problems | User 01 | High Beta | -0.7 | <0.05 |
| | | User 03 | Alpha Peak Frequency | 0.67 | <0.05 |
| | Sensory Subscale | User 01 | High Beta | -0.74 | <0.05 |
| Physical | Dizziness | User 01 | Delta | 0.75 | <0.05 |
| | | User 01 | Theta | 0.77 | <0.05 |
| | | User 01 | Alpha | -0.75 | <0.05 |
| | | User 01 | Low Beta | -0.89 | <0.01 |
| | | User 03 | Alpha Peak Frequency | 0.63 | <0.05 |
| | Physical Subscale | User 01 | Delta | 0.77 | <0.05 |
| | | User 01 | Theta | 0.76 | <0.05 |
| | | User 01 | Alpha | -0.68 | <0.05 |
| | | User 01 | Low Beta | -0.91 | <0.01 |
| | | User 03 | Alpha Peak Frequency | 0.63 | <0.05 |
| Cognitive | Disorientation | User 01 | Delta | 0.79 | <0.05 |
| | | User 01 | Theta | 0.76 | <0.05 |
| | | User 01 | Low Beta | -0.81 | <0.01 |
| | | User 03 | Theta | 0.67 | <0.05 |
| | | User 03 | Gamma | -0.78 | <0.01 |
| | Trouble Concentrating | User 01 | Delta | 0.81 | <0.01 |

| | | | | | |
|---|---|---|---|---|---|
| | | User 01 | Theta | 0.68 | <0.05 |
| | | User 01 | Low Beta | -0.81 | <0.01 |
| | | User 03 | Gamma | -0.67 | <0.05 |
| | Feeling Cognitively Sharp | User 01 | Delta | -0.73 | <0.05 |
| | | User 01 | Low Beta | 0.78 | <0.05 |
| | Feeling Mentally Taxed | User 01 | Low Beta | -0.77 | <0.05 |
| | Cognitive Subscale | User 01 | Delta | 0.84 | <0.01 |
| | | User 01 | Theta | 0.72 | <0.05 |
| | | User 01 | Low Beta | -0.91 | <0.01 |
| | | User 03 | Gamma | -0.77 | <0.01 |
| Combined | mTBI Symptom Score | User 01 | Delta | 0.83 | <0.01 |
| | | User 01 | Theta | 0.75 | <0.05 |
| | | User 01 | Low Beta | -0.92 | <0.01 |
| | | User 03 | Gamma | -0.8 | <0.01 |

## Real-Time EEG Changes During Blast Overpressure

Despite the challenges of interpreting dry EEG data in freely moving ambulatory participants, there were instances of observed increases in Theta power following blast exposure. User 01 exhibited this pattern following the first blast exposure on Day 1. Figure 7 below illustrates increased Theta activity approximately 10 minutes after blast exposure.

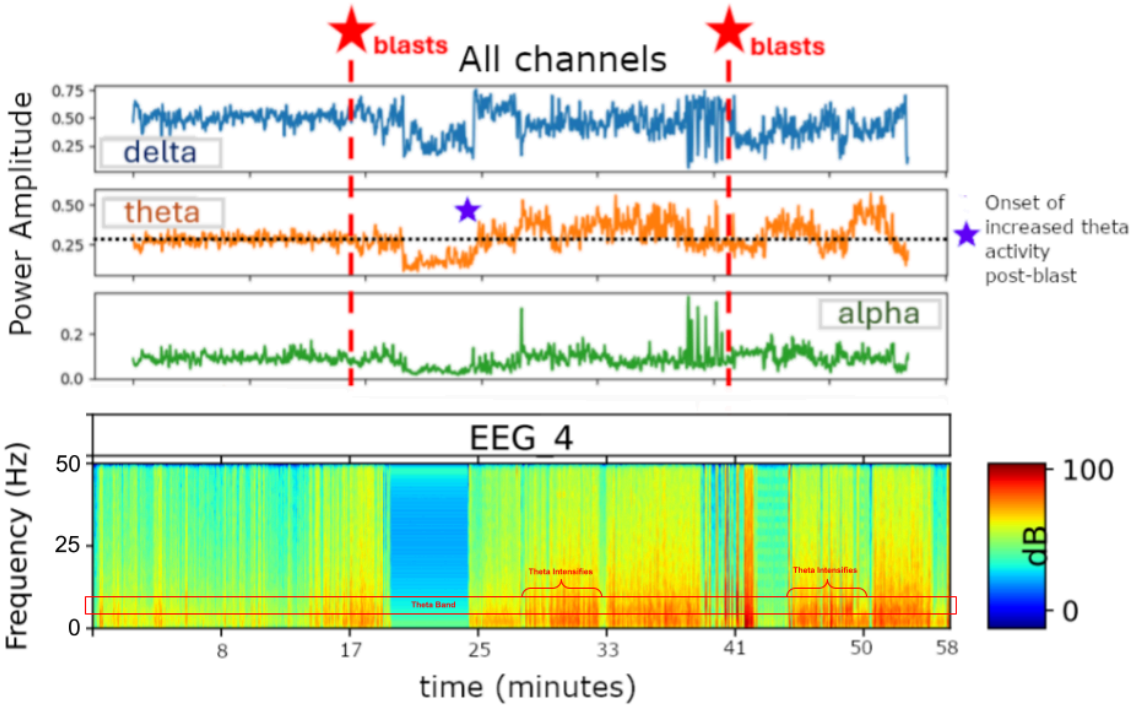

Figure 7. EEG data collected during live breaching from User 1 on Day 1 from Round 1. Top: averaged EEG signal from all device channels showing when blasts occurred and when an increase in Theta begins. Delta shows a smaller increase, while Alpha remains consistent in this session. Bottom: spectrogram from EEG channel 4. Blue block is a blast, and its signal disruption. The red box indicates the approximate range of the Theta Band, with the highlighted area showing increases in Theta power directly after blast exposure.

## Control Cohort Analysis

The largest signal changes for the control participants across Delta, Theta, and Alpha showed a random pattern compared with those for the blast participants, as shown in Figure 8. For all three bands, there was no consistent trend between participants in whether the signal increased or decreased, and changes remained minimal to moderate. For example, in Theta, controls 14 and 35 showed increases of 22 and 12 points, respectively, while control 411 showed a decrease of 32 points, and the blast participants all showed increases of at least 60 points.

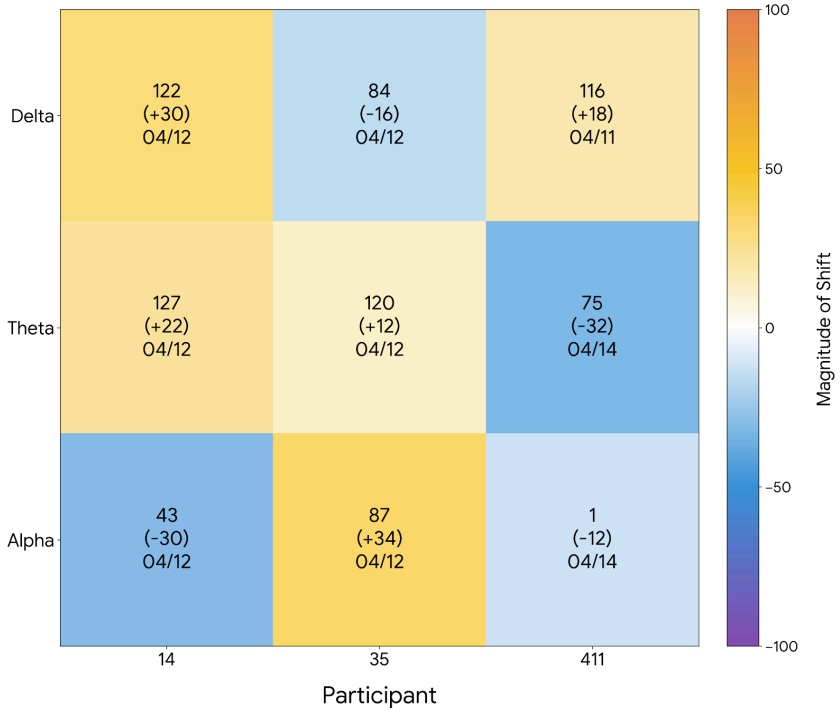


Figure 8: Heatmap displaying the greatest change in power band measurement from baseline session for participants not exposed to blast overpressure. The top value of the cell is the recorded measurement, the middle value is the change from baseline, and the bottom value is the date and session in which the greatest change was recorded.

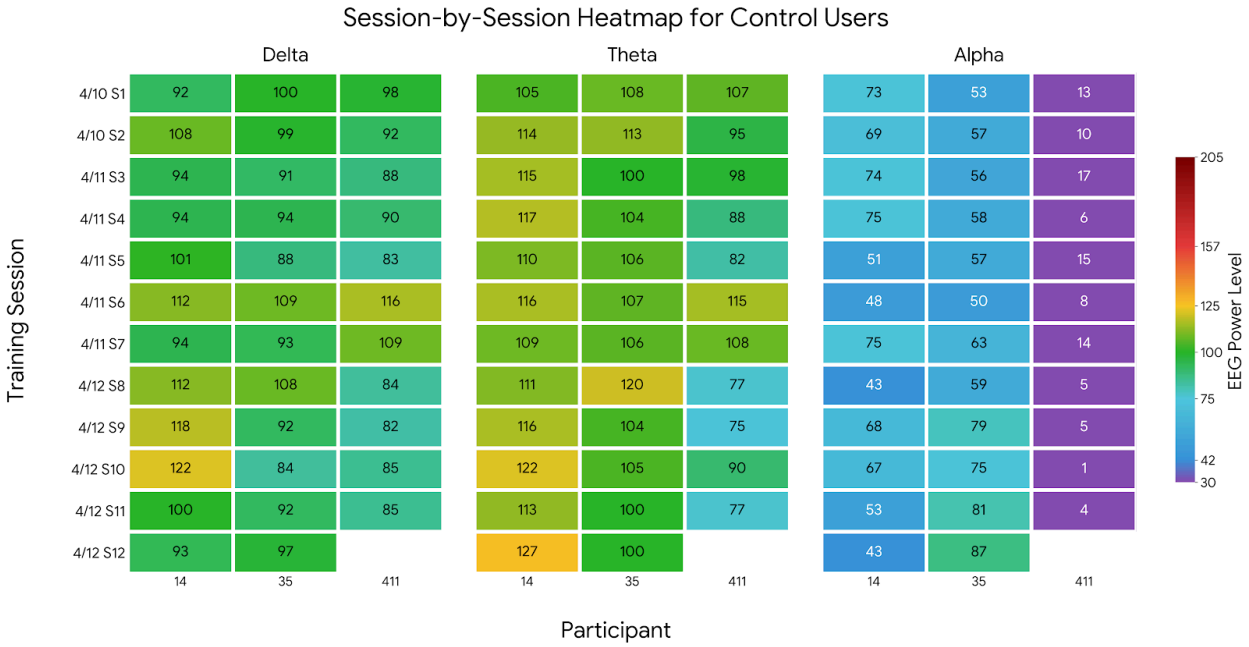


Figure 9. Heatmap displaying the per-session power band measurement for Delta, Theta, and Alpha across three days from participants who did not experience blast exposure.

Analysis of resting-state power-band metrics collected over three days revealed stable longitudinal trends in the control cohort that were typically consistent with population averages derived from the TD Brains dataset, as shown in Figure 9. Notably, the signals we found most correlated with blast exposure, Delta and Theta, remained within one standard deviation of the population mean, with a few session-isolated exceptions. Alpha, similar to the blast participant data, was consistently below the population mean by at least one standard deviation, though the magnitude of the difference varied across control participants and remained mostly consistent across sessions.

# Discussion

## Neural Signatures of Blast Exposure

The longitudinal increase in low-frequency power observed in this cohort mirrors the established spectral signatures of mild traumatic brain injury (mTBI). Literature indicates that the acute phase of mTBI (10 to 60 minutes post-injury) is characterized by increased Delta and Theta power, alongside reduced Alpha power[3]. Our results align closely with this profile. Specifically, the "dramatic" increase in Theta power observed across almost all participants, combined with the increase in delta and decrease in Alpha, suggests that the training environment generated a neural strain comparable to known injury models.

## The "Black Box" Window: 10–60 Minutes Post-Blast

A critical finding of this study is the temporal onset of these spectral changes. The real-time spectrogram reveals that Theta activity began to "ramp up" approximately 10 minutes following the first blast

exposure. This precisely corresponds with the 10-60 minute window identified in past literature as a critical period for metabolic and neural dysfunction[3].

In standard operational protocols, this window is often missed because assessment tools are applied hours or days after the event. By utilizing an EEG-integrated headset worn *during* the exercise, we successfully captured the onset of this neural shift. This validates the utility of "always-on" monitoring to detect transient physiological changes that retrospective assessments would likely overlook.

### Correlating Physiology with Function

The study also found significant correlations between quantitative EEG (qEEG) metrics and subjective behavioral reports, suggesting that these neural changes have functional consequences. For User 01, a consistent pattern emerged where increased physical and cognitive symptom severity correlated with elevated slow-wave activity (Delta and Theta) and suppressed Low Beta power, aligning with traditional models of post-concussive cortical slowing. In contrast, User 03's symptoms were more closely tied to shifts in Alpha Peak Frequency and Gamma suppression, suggesting that sensory and cognitive disruptions may manifest through different oscillatory mechanisms depending on the individual. These findings underscore the utility of intra-individual qEEG monitoring for identifying objective biomarkers of mTBI onset and recovery, while also highlighting the necessity of personalized baselines in clinical assessments.

### Implications for Early Detection

Past literature notes that epileptiform activity may occur in the first 1-2 minutes post-injury[3], a window that represents perhaps the most specific indication of TBI. While the 10-minute Theta ramp-up was the primary feature observed in this dataset, the capability to record continuously allows future applications to scrutinize this immediate 1-2 minute post-blast interval. The ability to automatically detect such immediate biomarkers could drastically improve the speed and accuracy of triaging personnel in the field, moving safety protocols from subjective reporting to objective physiological monitoring.

## Conclusion

This white paper details a pioneering effort to illuminate the "black box" of blast-induced neural strain. By integrating high-fidelity EEG sensors directly into standard-issue hearing protection, we successfully gathered the first-ever neural dataset covering the periods before, during, and after blast overpressure exposure.

The results validate that specific spectral changes, specifically an increase in **Theta** and **Delta** power, can serve as objective biomarkers for sub-concussive injury in the field. Crucially, the ability to detect the onset of these changes within the critical 10-to-60-minute post-blast window offers a distinct advantage over traditional, delayed assessments.

Moving forward, this technology presents a scalable solution for modernizing range safety. By transitioning from subjective self-reporting to objective, always-on physiological monitoring, military leadership can make data-driven decisions to mitigate cognitive risk and preserve force readiness.

## References


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