NeuroLullaby: Adaptive Bedtime Storytelling Using EEG-based Brain-Computer Interface for Sleep Health

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Abstract

Sleep disorders impact a significant portion of the global population, underscoring the need for innovative sleep assistance solutions. Traditional approaches, such as meditation apps and white noise, lack real-time adaptability to users' cognitive states. NeuroLullaby addresses this gap by integrating an EEG-based Brain-Computer Interface (BCI) with adaptive storytelling to enhance relaxation and improve sleep readiness. Leveraging consumer-grade EEG technology and advancements in Natural Language Processing (NLP) and Text-to-Speech (TTS), NeuroLullaby dynamically tailors narrative elements based on the user's relaxation levels. The effectiveness of NeuroLullaby is evaluated through a user study, demonstrating significant relaxation improvements compared to non-adaptive approaches. These findings suggest its potential as an effective sleep aid with broader therapeutic applications, contributing a novel neuroadaptive system architecture advancing personalized solutions in sleep health.

CCS Concepts

• **Human-centered computing → HCI design and evaluation methods**; **Empirical studies in HCI**; *Interaction design process and methods*; • **Applied computing** → *Consumer health.*

Keywords

EEG-based brain-computer interface (BCI), adaptive storytelling, sleep health, real-time neurofeedback, human-computer interaction (HCI), text-to-speech (TTS)

1 Introduction

Sleep quality is a critical aspect of overall health, yet many individuals struggle with sleep disorders that impact daily functioning and long-term well-being. Traditional sleep assistance methods, such as meditation apps and white noise generators, are limited by their inability to adapt to individual cognitive states in real time. This limitation calls for innovative approaches that provide personalized and dynamic solutions. NeuroLullaby addresses this gap by integrating an EEG-based Brain-Computer Interface (BCI) with adaptive storytelling, aiming to enhance relaxation and improve sleep readiness.

NeuroLullaby leverages advancements in consumer-grade EEG technology, Natural Language Processing (NLP), and Text-to-Speech (TTS) systems to create a novel sleep aid. By dynamically tailoring narrative elements—including content, pacing, and voice modulation—based on real-time EEG data, the system delivers a personalized storytelling experience that promotes relaxation. This neuroadaptive approach sets NeuroLullaby apart from static sleep assistance tools and introduces a potential breakthrough in addressing individual sleep challenges.

This report details the development and evaluation of NeuroLullaby. It begins with a review of existing work in adaptive storytelling, EEG-based systems, and sleep health technologies, followed by an overview of the system architecture and implementation. The evaluation section presents findings from a user study, demonstrating NeuroLullaby's impact on relaxation and sleep preparation. Finally, we discuss the broader implications of this work for personalized therapeutic applications and future advancements in neuroadaptive systems.

2 Literature Review

The development of NeuroLullaby draws on research in adaptive storytelling, EEG-based neurofeedback, and music's role in emotional regulation. Foundational work by Cavazza et al. [1] introduced adaptive storytelling systems that modify narratives in response to real-time user feedback, demonstrating the potential for creating personalized and engaging experiences. Building on this, NeuroLullaby uses EEG data to tailor storytelling tone, pace, and auditory elements specifically for relaxation.

Research on music and its emotional effects further supports NeuroLullaby's design. Zatorre and Salimpoor [6] explored the neural mechanisms behind music-induced emotional responses, highlighting its potential for relaxation and emotional self-regulation. Similarly, Cui et al. [2] reviewed EEG-based music emotion recognition, emphasizing the feasibility of real-time adaptations. These insights are integral to NeuroLullaby's dynamic use of background music, enhancing its emotional and relaxing effects.

EEG neurofeedback studies reinforce the validity of this approach. Enriquez-Geppert et al. [3] demonstrated the effectiveness of EEG protocols for relaxation, while Thibault and Raz [5] noted the psychological impacts of neurofeedback, even when influenced by placebo effects. These findings affirm the use of EEG-based feedback to promote relaxation through adaptive storytelling and music.

Further contributions from immersive EEG applications provide valuable insights. Zhang et al. [7] confirmed the reliability of EEG for measuring and supporting relaxation in adaptive systems, while Li et al. [4] showcased the BEAMERS system, which uses EEG signals to predict emotional states and adjust music in real time. These studies demonstrate the potential of EEG-driven interventions for personalized emotional regulation, closely aligning with NeuroLullaby's objectives.

3 System Architecture and Design

3.1 Overview

The NeuroLullaby system integrates hardware and software components to create an adaptive bedtime storytelling application.

As illustrated in Figure 1, the system leverages real-time EEG data from a brain-computer interface (BCI) to adjust storytelling parameters, such as tone, pitch, and speed, based on the user's relaxation levels. This neuro-interactive approach is intended to promote relaxation and enhance sleep quality. NeuroLullaby comprises three primary components: the EEG device for data acquisition, software modules for adaptive text-to-speech (TTS) and story generation, and a user interface (UI) for user interaction.

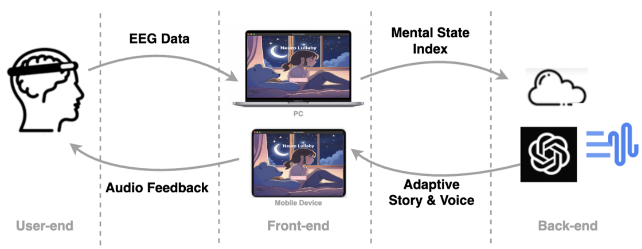

Figure 1: System Framework of NeuroLullaby: The figure illustrates how EEG data is processed to generate adaptive stories, where user relaxation levels dynamically influence storytelling parameters for a personalized experience.

3.2 Hardware component: EEG Device

The hardware foundation of NeuroLullaby is the BrainCo HeadBand, an EEG-based BCI device designed for capturing brainwave data. This device measures electrical activity in the brain, providing real-time metrics on the user's mental states, particularly relaxation and focus. Key features and specifications of the EEG device include:

- **EEG signal acquisition:** The BrainCo HeadBand captures EEG signals from the user's forehead region, which are indicative of various cognitive states.
- **Data processing:** The device preprocesses raw EEG signals using a Butterworth Filter to filter the EEG signal and generate relaxation scores. It calculates relaxation scores through the normalized ratio of the sum of α band (8-13 Hz, associated with relaxation) and γ band (30-60 Hz, associated with high-level cognitive processing) energies from their spectrograms over β band (13-30 Hz, associated with active thinking and focus) energy. The metrics are smoothed using a sliding window. These metrics are transmitted to the NeuroLullaby application through a wireless connection, enabling real-time interaction.
- **Compatibility:** The BrainCo HeadBand supports integration with software applications via APIs, making it suitable for NeuroLullaby's adaptive storytelling functionality.

3.3 Software Components

The NeuroLullaby software ecosystem consists of several interdependent modules that enable adaptive audio storytelling based on EEG input. These modules include text-to-speech (TTS) processing, Natural Language Processing (NLP) for dynamic storytelling, and the User Interface. Together, these modules ensure that NeuroLullaby can adjust the storytelling experience in response to changes in the user's mental state.

3.3.1 Text-to-Speech (TTS) Module. The TTS module is a core component responsible for converting text-based story content into natural-sounding audio. NeuroLullaby uses the Google Cloud Text-to-Speech API, which provides high-quality voice synthesis with options to adjust voice parameters. Key aspects of the TTS module include:

- **Voice selection:** The TTS module allows the user to choose between male and female voices, with predefined voices (e.g. "en-US-Wavenet-J" for male and "en-US-Wavenet-F" for female) optimized for bedtime storytelling.
- **Parameter adjustments:** Based on EEG relaxation scores, the TTS module dynamically adjusts audio parameters such as pitch, speaking rate, and volume gain:
  - *Pitch:* Adjusted to create a soothing or engaging tone depending on the user's relaxation level.
  - *Speaking rate:* Slower speaking rates are applied as the user's relaxation level increases, fostering a calming effect.
  - *Volume gain:* Volume is modified to complement the storytelling ambiance, supporting the listener's state of mind.

3.3.2 Natural Language Processing (NLP) and Dynamic Story Generation. The storytelling experience in NeuroLullaby is further enhanced by the integration of OpenAI's GPT-based Natural Language Processing. This module generates story content dynamically, allowing the narrative to evolve based on the user's relaxation levels. The NLP module's key functions include:

- **Story generation:** The OpenAI GPT API creates additional story segments tailored to the user's current state. For instance, if the relaxation level is high, the story may progress in a calm, positive direction. Conversely, if relaxation decreases, the story may introduce engaging elements to recapture attention.
- **Contextual adaptation:** The story is not static but adjusts contextually, using prompts that reference the user's relaxation state. This interactive element ensures that the story remains engaging and relevant to the user's cognitive state.
- **Integration with EEG feedback:** EEG data is continuously fed into the NLP module, enabling the generation of story content that reflects the user's current level of engagement and relaxation.

3.3.3 User Interface (UI). The UI component of NeuroLullaby is designed to provide a user-friendly and intuitive experience, enabling users to interact with the app and monitor their relaxation in real time. The UI is developed using the Kivy and PyQt5 frameworks, offering a cross-platform, visually appealing interface. Key features of the UI include:

- **Voice selection and story initiation:** The initial screen allows users to select their preferred voice and start the storytelling session. Users can choose between a male or female voice to suit their preference, providing a personalized storytelling experience. The design aims to create a calming atmosphere, with soft colors and a bedtime theme to encourage relaxation from the very beginning of the session.
- **Real-time EEG feedback visualization:** The UI displays EEG-derived relaxation scores, allowing users to observe their relaxation state (e.g. "Active," "Calm," "Relaxed," "Deeply Relaxed") in real time. This feedback helps users become more aware of their mental state and progress toward relaxation.
- **Multi-screen interface:**
  - *Screen 1:* Voice selection and story initiation options.
  - *Screen 2:* Real-time visualization of EEG data, showing relaxation scores and state transitions.
  - *Screen 3:* A "Good Night" screen that appears when the user reaches a "Deeply Relaxed" state for 10 seconds, signaling readiness for sleep.

Figure 2 illustrates two distinct panels. The left panel represents the behind-the-scenes EEG data monitoring and processing interface, which captures raw EEG signals, attention, and meditation levels in real time. This detailed monitoring allows for precise adaptation of the storytelling experience. The right panel is the user-facing UI, where users experience the adaptive storytelling interface. It provides feedback on the user's relaxation score and relaxation state, offering a calming and engaging bedtime story.

4 Experiment

The NeuroLullaby project aimed to evaluate the effectiveness of adaptive storytelling, driven by real-time EEG feedback, on promoting relaxation in users. To achieve this, a structured user study was conducted with multiple trials, both with and without NeuroLullaby's audio feedback, to compare the effects on participants' relaxation levels. The study employed two main metrics, Mean Relaxation Index (MRI) and Proportion of Time with Relaxation Index Above 40 (Above_40_Ratio), to quantify relaxation and assess the significance of observed differences through statistical analysis.

4.1 User Study Design

The user study involved five participants, each undergoing four trials that alternated between conditions with and without audio feedback. The objective was to measure relaxation under both conditions and determine if NeuroLullaby's adaptive storytelling led to a statistically significant increase in relaxation.

4.1.1 Participants. Five participants, ages 24 to 38, took part in the study. All participants were briefed on the purpose of the study and provided consent to participate. No strict inclusion or exclusion criteria were applied in terms of participants' sleep habits, health conditions, or prior experience with relaxation techniques.

4.1.2 Setup and Trial Conditions. Each trial was conducted in a quiet, controlled environment to minimize external distractions and ensure optimal conditions for relaxation. Participants were seated comfortably and equipped with the BrainCo HeadBand, an EEG-based brain-computer interface calibrated to monitor real-time brainwave data, specifically focusing on relaxation levels.

The experiment consisted of four five-minute trials alternating between conditions with and without NeuroLullaby's adaptive storytelling audio. In trials with audio, participants listened to the storytelling through headphones to ensure an immersive experience. During trials without audio, participants were instructed to close their eyes and relax independently. EEG relaxation scores were recorded continuously in a `.csv` file for subsequent analysis. The trial conditions were as follows:

- **Trial 1 (without audio):** Participants relaxed without any audio feedback.
- **Trial 2 (with audio):** Participants listened to NeuroLullaby's adaptive storytelling, with audio dynamically adjusted based on EEG relaxation scores.
- **Trial 3 (without audio):** A repeat of Trial 1 to observe relaxation changes over time without audio feedback.
- **Trial 4 (with audio):** A repeat of Trial 2 to evaluate cumulative effects of NeuroLullaby's adaptive storytelling.

4.2 Metrics

To quantify the effectiveness of NeuroLullaby's adaptive storytelling, two primary metrics were calculated for each trial:

4.2.1 Mean Relaxation Index (MRI). The Mean Relaxation Index (MRI) represents the average relaxation level across each trial. Higher MRI values indicate greater relaxation, providing a direct measure of NeuroLullaby's impact on the participant's relaxation state.

- **Calculation:** MRI is calculated by taking the average of all relaxation scores recorded during each trial.

$$\text{MRI} = \frac{\sum_{i=1}^{n} \text{Relaxation Score}_i}{n} \tag{1}$$

  where n is the total number of scores (300 for each five-minute trial).
- **Interpretation:** Higher MRI values indicate greater relaxation. An increase in MRI between trials without audio and with audio feedback indicates a positive effect of NeuroLullaby on relaxation.

4.2.2 Proportion of Time with Relaxation Index Above 40 (Above_40_Ratio). The Above_40_Ratio measures the proportion of time during each trial when the relaxation score was greater than 40, a threshold indicative of moderate relaxation.

- **Calculation:** Above_40_Ratio is calculated as the percentage of seconds within each trial where the relaxation score exceeded 40, divided by the total trial duration (300 seconds).

$$\text{Above\_40\_Ratio} = \frac{\sum_{i=1}^{n} (\text{Relaxation Score}_i > 40)}{n} \tag{2}$$

- **Interpretation:** A higher Above_40_Ratio indicates that participants were able to maintain higher relaxation levels for a greater proportion of the trial.

Figure 2: Behind the Scenes of NeuroLullaby: The left panel represents the internal EEG data monitoring interface, while the right panel shows the user-facing adaptive storytelling interface. The right panel dynamically reflects the user's relaxation state, aiming to foster an immersive and soothing experience.

4.3 Statistical Analysis

To determine the significance of differences in relaxation levels between trials with and without audio feedback, a paired t-test was used for each metric (MRI and Above_40_Ratio). The paired t-test is appropriate here because each participant completed trials under both conditions, allowing for a within-subject comparison.

4.3.1 Paired Sample t-Test. A paired sample t-test was conducted for each metric to test the hypothesis that NeuroLullaby's audio feedback leads to greater relaxation.

- **Hypotheses:**
  - **Null Hypothesis (H_0):** There is no significant difference in relaxation levels between trials with and without audio feedback.
  - **Alternative Hypothesis (H_1):** There is a significant difference in relaxation levels between trials with and without audio feedback.
- **Significance Level (α):** A significance level of 0.05 was used, meaning that a p-value below 0.05 would indicate a statistically significant difference between the two conditions.

4.3.2 Statistical Metrics. For each metric (MRI and Above_40_Ratio), the following statistical values were computed:

- **Mean and Standard Deviation:** Calculated for each condition (with audio and without audio) to compare central tendencies and variability.
- **t-Statistic:** Reflects the difference in means between the two conditions relative to the variability of the differences.
- **p-Value:** Indicates the probability of observing the results under the null hypothesis. A p-value below 0.05 indicates that NeuroLullaby's audio feedback has a statistically significant effect on relaxation.

4.4 Data Visualization

The data from each trial was visualized to illustrate changes in relaxation levels over time and to compare conditions with and without audio feedback. Key visualizations include:

- **Line Graphs:** For each participant, line graphs were generated to show relaxation levels over time across all four trials. This visual representation helps to identify trends and contrasts between trials with and without NeuroLullaby's audio feedback.
- **Summary Graphs:** Aggregated results for MRI as well as for Above_40_Ratio were visualized to compare overall relaxation across conditions.

5 Results

This section presents the results of the NeuroLullaby user study, analyzing how adaptive storytelling affects user relaxation. Two primary metrics were calculated: Mean Relaxation Index (MRI) and Proportion of Time with Relaxation Index Above 40 (Above_40_Ratio).

Descriptive statistics and paired t-tests were used to evaluate the significance of the difference in relaxation levels between trials with and without NeuroLullaby's audio feedback.

5.1 Mean Relaxation Index (MRI)

Mean Relaxation Index (MRI) represents the average relaxation score across each trial. Higher MRI values indicate greater relaxation and provide a direct measure of the impact of NeuroLullaby's audio feedback on participants' relaxation levels.

5.1.1 Individual Subject Data. Table 1 shows the MRI values for each participant across conditions with and without audio feedback.

Table 1: Mean Relaxation Index (MRI) for each participant with and without audio feedback

Subject	Without Audio	With Audio
1	26.49	47.64
2	28.16	49.66
3	0.00	36.56
4	20.46	18.94
5	31.93	54.41

In most cases, MRI values were higher with audio feedback, suggesting that NeuroLullaby's adaptive storytelling positively affected relaxation. Subject 4 was the only participant who showed a slight decrease with audio feedback.

5.1.2 Statistical Summary.

- **Without audio:** 21.41 ± 11.33
- **With audio:** 41.44 ± 12.68
- **Mean difference (with - without):** 20.03

These statistics indicate that the average relaxation level across participants was higher during trials with audio feedback than during silent trials, with a mean increase of 20.03 points in MRI.

5.1.3 Paired t-Test Results. A paired t-test was conducted to assess the significance of the difference in MRI between conditions with and without audio feedback:

- **t-Statistic:** -3.276
- **p-Value:** 0.031
- **Significance:** Yes ($\alpha = 0.05$)

The p-value of 0.031 is less than the significance level of 0.05, indicating that the difference in MRI between audio and silent trials is statistically significant. This suggests that NeuroLullaby's adaptive storytelling has a significant positive effect on relaxation.

5.1.4 Interpretation. The results indicate that the Mean Relaxation Index (MRI) was consistently higher in the audio condition across most participants, supporting NeuroLullaby's ability to enhance relaxation. Table 1 reflects this increase, showing an overall higher average relaxation level when audio feedback was provided compared to silent trials. These findings align with the hypothesis that personalized, real-time storytelling can effectively improve relaxation states. The statistically significant difference, with higher MRI values during audio trials, demonstrates that NeuroLullaby's adaptive feedback has a positive impact on participant relaxation.

5.2 Proportion of Time with Relaxation Index Above 40 (Above_40_Ratio)

The Above_40_Ratio metric represents the proportion of time during each trial that the relaxation score exceeded 40, indicating periods of moderate relaxation. This metric reflects the consistency of relaxation achieved with NeuroLullaby.

5.2.1 Individual Subject Data. Table 2 shows Above_40_Ratio values for each participant across conditions with and without audio feedback.

Table 2: Proportion of Time with Relaxation Index Above 40 (Above_40_Ratio) for each participant with and without audio feedback

Subject	Without Audio	With Audio
1	0.21	0.68
2	0.00	0.72
3	0.26	0.36
4	0.00	0.07
5	0.22	0.83

Most participants spent a greater proportion of time in a relaxed state when listening to NeuroLullaby, with notable increases for Subject 1, Subject 2, and Subject 5.

5.2.2 Summary Statistics.

- **Without audio:** 0.14 ± 0.12
- **With audio:** 0.53 ± 0.28
- **Mean difference (with - without):** 0.39

These summary statistics indicate that the proportion of time spent in a relaxed state was significantly higher in trials with NeuroLullaby's audio feedback, with an average increase of 0.39 in the Above_40_Ratio.

5.2.3 Paired t-Test Results. A paired t-test was performed to compare Above_40_Ratio values between conditions:

- **t-Statistic:** -2.947
- **p-Value:** 0.042
- **Significance:** Yes ($\alpha = 0.05$)

The p-value of 0.042, below the significance level of 0.05, suggests that the increase in Above_40_Ratio with audio feedback is statistically significant. This finding supports the effectiveness of NeuroLullaby's adaptive storytelling in helping participants maintain relaxation over longer durations.

5.3 Summary of Findings

The results of the NeuroLullaby user study indicate that adaptive storytelling has a significant positive impact on relaxation levels. Key findings include:

- **Increased Mean Relaxation Index (MRI):** The average MRI was significantly higher during trials with NeuroLullaby's audio feedback, suggesting enhanced relaxation.
- **Higher Proportion of Time in a Relaxed State:** The Above_40_Ratio was significantly higher in trials with audio

feedback, indicating that NeuroLullaby helps sustain relaxation.
- **Statistical Significance:** Paired t-tests confirmed significant differences for both metrics, demonstrating that NeuroLullaby's adaptive storytelling effectively promotes relaxation.

5.4 Limitations

While the results are promising, certain limitations should be noted:

- **Small Sample Size:** The study's small sample size limits the generalizability of the findings. A larger sample would provide more robust evidence of NeuroLullaby's effectiveness.
- **Individual Variability:** Some participants responded more positively to NeuroLullaby than others. Further research is needed to understand factors that influence individual responses to adaptive storytelling.
- **Controlled Environment:** The trials were conducted in a controlled environment, which may differ from real-world settings where NeuroLullaby would typically be used.

6 Discussion

6.1 Key Findings and Implications

Our user study demonstrates NeuroLullaby's significant positive impact on relaxation levels through both metrics. The substantial increase in MRI (from 21.41 ± 11.33 to 41.44 ± 12.68, $p = 0.031$) during trials with audio feedback indicates successful induction of deeper relaxation states. Similarly, the improvement in Above_40_Ratio (from 0.14 ± 0.12 to 0.53 ± 0.28) demonstrates the system's ability to maintain sustained relaxation, crucial for sleep preparation. Individual variations in response—with four out of five participants showing marked improvement—highlight the importance of personalization in relaxation technologies. The successful integration of real-time EEG data with adaptive storytelling validates our approach to story adaptation, where narrative elements and voice parameters dynamically respond to users' cognitive states. The BrainCo HeadBand proved effective in capturing and transmitting relaxation metrics, demonstrating the viability of brain-computer interfaces for sleep health applications.

6.2 Future Work

While promising, our study has several limitations:

- Small sample size ($n = 5$) limiting generalizability
- Controlled environment not reflecting real-world usage
- Limited duration of trials

Future work should address these limitations through:

- Larger-scale studies with diverse demographics
- Enhanced personalization algorithms and voice parameters
- Testing in actual bedroom environments with longer durations
- Integration with sleep monitoring for long-term tracking

6.3 Broader Applications

NeuroLullaby's success suggests potential applications beyond individual sleep assistance, including clinical therapy, stress reduction programs, and meditation practices. The successful integration of BCI technology demonstrates possibilities for broader wellness applications, from educational tools to therapeutic interventions.

7 Conclusion

This research has demonstrated the effectiveness of combining EEG-based brain-computer interfaces with adaptive storytelling for sleep assistance. Through NeuroLullaby, we have shown that real-time neuroadaptive content delivery can significantly enhance relaxation states, creating a continuous feedback loop between cognitive state and storytelling experience. Our empirical results, showing a nearly twofold increase in mean relaxation indices (from 21.41 to 41.44) and significantly improved sustained relaxation periods (Above_40_Ratio increasing from 0.14 to 0.53), validate the effectiveness of this approach.

Despite limitations in sample size and study duration, our findings suggest several promising directions for future development. The observed individual variations in user response highlight opportunities for enhanced personalization algorithms, while the successful integration of BCI technology demonstrates potential applications beyond sleep assistance, including therapeutic and wellness contexts. Key contributions include:

- A novel architecture integrating real-time EEG feedback with adaptive storytelling
- Empirical validation of neuroadaptive content delivery for relaxation
- Implementation strategies for cognitive state-based story generation
- Insights into individual variations in response to adaptive relaxation tools

As consumer-grade BCI technology evolves, systems like NeuroLullaby represent an important step toward personalized sleep health solutions, with future work focusing on larger-scale studies and enhanced personalization features.

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