Real-time Sensing and NeuroFeedback for Practicing Meditation Using simultaneous EEG and Eye Tracking

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***Abstract*—Next-generation intelligent health-monitoring systems have been ushered in by mobile phones with robust computation power, affordable high-resolution cameras, and embedded wearable sensors. Wearable Electroencephalography (EEG) headset to record brain signals with simultaneous eye tracking using a mobile front camera can become a powerful tool to modulate brain activity for self-enhancement. Meditation has been proved to have great effects in neuroscientific investigations for decades. However, a naive practitioner initiates the practice with high motivation and steps down after struggling to get the feedback or follow the instructions. EEG headset and Eye-tracking technology can help beginners get real-time audio and visual feedback and encourage those who fail to continue a regular meditation session. This article proposes real-time feedback framework for generating mindful moments and trace progress while practicing. Three major components are: Learning Phase, Meditation Style Specific Feedback and Evaluation Phase. We discuss three learning moments including preparatory, disentanglement and mindful. This study facilitates the design of a neurofeedback product that can offer tailored feedback. Neurotechnological revolution enables individuals to attain better equilibrium, sustained attention, metacognitive awareness, decreased mind-wandering, and enhanced emotional stability through various meditation practices.**

***Index Terms*—Machine Learning, EEG, Wearable Sensors, Eye Tracking, Deep Learning, Mindfulness, Meditation**

I. Introduction

The sensor market is expected to create potential incremental opportunities worth $100 Bn by 2026 due to advancements in sensor technology and application in several end-use industries. [1]. Consumer wearable sensor technology has been growing significantly in the last decade and opens a plethora of opportunities for the health and wellness industry [2]. A wide range of consumer-grade health-monitoring devices is available in the market that can record biological activity to monitor various aspects of lifestyle and provide feedback to maintain self-care [3]. Sensor technology generates a lot of data that can be used in several ways for healthcare and wellness.

Meditation as a mental practice that is regarded as a collection of distinct attentional involvement, emotional and self-regulation, with increased sensory and meta-awareness [4]. However, in today's time to improve and initiate meditation practice, there is far less understanding on which meditation techniques and steps are suitable for the individual to objectively determine the degree of consistency and compliance with the instructions, particularly in the initial stages of practising meditation. [5]. Hence, real-time neurofeedback (auditory and visual) to naive practitioners with the desired meditation technique would enhance practical usage of these neurotechnological applications to practice prolonged meditation among naive users. This is the hour of the need as this neurotechnological revolution to practice meditation can help individuals attain better equilibration, sustained attention, metacognitive awareness, decreased mind-wandering, and enhanced emotional stability through various meditation practices.

Brain signals deliver insights into our thoughts, perception, and many other aspects of cognition. There are several brain imaging techniques, including Electroencephalography (EEG), functional Magnetic Resonance Imaging (fMRI), and Magnetoencephalography (MEG). However, EEG is the most pervasive technology available outside the lab or clinical settings for consumer use. Human visual attention can be measured externally through gaze tracking, and initial studies have gone back to recording it in the eighteenth century [6], [7].

Increasing sensor technology provides massive data for deep learning training to generate latent patterns and further enhance healthcare AI products. Artificial Intelligence has been inspired by the human brain and recent advancements in deep learning are a reflection of how information processing would happen in the brain. Signals captured using neuroimaging techniques

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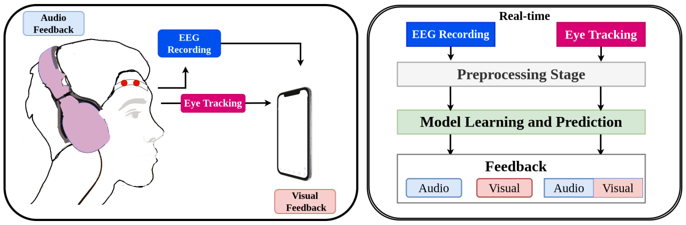

Fig. 1. []Left] EEG headset wearable by an individual to obtain neural signals, and front cameras use for eye tracking. Real-time feedback is provided in three ways: audio, visual, and combining audio and video. [Right] Real-time processing pipeline contains three stages, starting with preprocessing the incoming data, followed by predicting the user's brain state, and the last step is providing feedback based on the state observed.

preserve several patterns, which can be decoded as a hierarchical structure using deep learning techniques. This research uses EEG and eye tracking data to predict the user's cognitive states and exploration of visual attention.

We focus to develop Mindfulness Kit based on real-time feedback using consumer EEG and eye tracker. In this article, we primarily focus on a particular component, proposing neuro-feedback framework involving brain and gaze data to navigate a user to reach mindful moments. Therefore, we discuss the following three major components to get feedback for specific technique with assessment method.

1) Learning Phase : Experiencing the three moments (preparatory, disentanglement, mindful) while practicing meditation.
2) Meditation Specific Feedback : Individual can practice three broad meditation techniques (Focused Attention, Open Monitoring, Loving-Kindness) based on their preferences.
3) Evaluation Phase: Post training can be assessed by various established scale such as Sustained Attention to Response Task (SART), Compassion scale etc to observe sustained attention, emotional regulation,and other cognitive measures.

II. Methodology

The neuro-feedback flow has shown in Fig. 1. Brain signals are captured using a wearable EEG headset and gaze data from the front camera. Real-time data processing is followed by the preprocessing stage and fed into the model for learning and predicting brain state. Based on the prediction, audio and visual feedback can be provided.

A. Wearable EEG and Mobile Eye Tracking

Electroencephalography (EEG) is widely employable non-invasive methodology to record neural signals [17]. In the past, the large hardware setup was only restricted to clinics or labs to monitor subjects or collect data on experimental design. There has been a huge growth in brain imaging technology in the last few decades due to extensive research efforts, and non-invasive portable EEG has been put into use for out-of-lab scenarios. Portable EEG is quite successful in getting data with few channels, and it is not a replacement for professional-grade EEG systems, but this can be used with few channels in real-world settings to capture some cognitive mechanisms. Recently, several articles have been published utilizing portable EEG for analyzing meditative brain waves and providing neurofeedback [18]–[20]. EEG feedback system for meditation has made a significant space in the industry, and several companies are designing products for consumers to experience meditative states [21]. Gaze tracking has been used in several applications across many domains, including human-computer interaction, medical diagnosis, and behavioral studies. [22]–[24]. In contrast to portable EEG, mobile eye tracking is not up to the mark for accurate evaluation and performs badly in real-world settings. However, recently there has been significant growth in this field and may get improve in the near future and will be a pervasive technology on smartphones [25]. Eye tracking methodology has been used to identify the relationship between mindfulness and attention in various studies [15], [26].

B. Preprocessing Stage

Data collected from EEG and Eyetracking bring a lot of noise. Raw signals must be processed before passing to the learning models to generate inference from data. The spotlight of recent study is on preprocessing to improve the signal-to-noise ratio and illustrate the Muse EEG denoising pipeline workflow [27]. The Harvard Automated Processing Pipeline for Electroencephalography (HAPPE) employs wavelet-based filtering and gives a standardised post-processing report to assess data quality [28]. Multiple Artifact Rejection Algorithm (MARA) is a machine learning-based filtering technique that assigns a probability to an independent component and flags the artifactual signal. In recent work [25], deep learning model for eye tracking has shown to be very effective.

C. Model Learning and Prediction

Over the past years, learning and statistical techniques have contributed significantly in decoding the classification of different stages of meditation, which may serve as a backbone to provide real-time neurofeedback and few articles are shown in Table I. Wavelet families were used in a recent study to extract features that differentiated expert and non-expert meditators, which were then categorised using twelve machine learning classifiers [9]. Wavelet orders Bior3.5 and Coif5 showed the maximal classification using coefficients d8 that corresponds to theta waves. In a similar line of work, [14], topographical plots of brain responses were fed into Convolution Neural Network to classify the stages among control, expert, and non-expert. Recent work discussed EEG data recorded before and after Mindfulness-Based Stress Reduction(MBSR) training, followed by feature extraction utilizing three non-linear dynamics to derive the significance of the scalp regions using the SHAP explainable model. A recent review paper discusses a broad spectrum of mental states generated during meditation

TABLE I
CLASSIFICATION OF STATES USING ML AND STATISTICAL TECHNIQUES

Article	Modality	Classification	Feature	Method
Grandchamp (2014) [8]	Eye Tracking	Mind Wandering Vs. Breath-Focus	Mean Pupil Size	SVM
Pandey et al. (2020) [9]	EEG	Expert Vs. Non-Expert Meditators States	Entropy, Power	Gaussian Process, QDA
Vivot et al. (2020) [10]	EEG	Three meditation Traditions: Vipassana, Himalyana Yoga, Isha Sooniya	Entropy	Random Forest
Sharma et al. (2021) [11]	EEG	Meditator Vs. Non-Meditators	Statistical Parameters	SVM, Decision Tree
Dong et al. (2021) [12]	EEG	Mind-wandering detection	ERP	SVM, Logistic Regression
Pandey et al. (2021) [13]	EEG	Pre Vs. Post Mindfulness 8 week session	Fractal Dimension	Random Forest with SHAP
Pandey et al. (2021) [14]	EEG	Control Vs. Expert Vs. Non-Expert Meditative States	Topograph Plots	Deep CNN, VGGNET, RESNET
Ford (2021) [15]	Eye Tracking	Trait Mindfulness and Visual Attention	Dwell Time	CMAS-R, FFMQ
Kora et al. (2021) [16]	EEG	Review on EEG based interpretation on meditation using Machine Learning	Linear and Non-Linear	ML and DL

and further classifying using several machine learning techniques [16]. There is ample opportunity to employ state-of-the-art deep learning techniques including graph neural networks, self-supervision, attention networks, and transformers. Few classification problems are mentioned below that would be included for all meditation techniques:

1) Breath Focus Vs. Mind Wandering
2) Low Drowsiness Vs. High Drowsiness
3) Breath Focus (Low Drowsiness) Vs. Other Drowsiness States
4) Mind Wandering (Low) Vs. Mind Wandering (High)

D. Neuro Feedback

Models receive the data and predict the participant's mental state, and based on the state, feedback can be designed to help the naive practitioner know their mental state. Several neural markers are discussed here [29].

1) Audio: Recent studies have shown that auditory feedback enhances mindful experiences and provides many opportunities to explore the suitable audio clips to be used for mindfulness moments [30]. For instance, if a person's mind wanders, then instant neurofeedback can be provided with audio that makes the user aware of the mind wandering moments and a soothing sound for a calm state of mind.

2) Visual: Feedback can be provided using various animations and visuals for guiding a participant to feel relaxed and attain a mindful state [31]. Virtual reality technology has enabled to the enhancement of mindfulness skills and training [32]. Eye tracking can be effectively used to help the user focus on a particular visual and can involve several attention-related cognitive designs to train a person's sustained attention.

3) Audio+Visual: EEG and Eye-tracking can be used effectively to generate simultaneously to record the person's brain signals and gaze behavior, which can supplement each other to provide the best experience of mindful moments.

III. PROPOSED FRAMEWORK

In this, we propose a framework to get the feedback based on the real-time collected data, as shown in Fig. 2.

A. Learning Phase

The first step in the learning phase is practicing meditation, which consists of three distinct moments. Three moments can be examined and then segmented into different moments based on the data, as shown in Fig. 3.

1) Preparatory Moments: This is the initial stable state of the individual which is being measured as a baseline state. It will help participants feel relaxed when they will later see their progress in comparison to baseline state, before diving deeper into the mindful moments.

2) Disentanglement Moments: A state majorly involves identifying disentanglement and the engagement of thoughts and to bring focus on the goal of the meditation and the mind to a restful state. For instance, disentanglement moments can describe the score for mind-wandering and focused attention. It will identify the task-unrelated moments of the participants caused by external and internal stimuli.

3) Mindful Moments: This state includes the calm and intense experience of Mindfulness, with moments of deep relaxation. Practitioners will feel more aware of their mindful states leading to enhanced interoceptive perception, sustained focused meditation, positive affective states by making a choice for practice of the the specific meditation tradition module. Here, participants require sustained and consistent practice to reach enhanced states of mindful moments.

B. Meditation Specific Feedback

Learning phase is the comprehensive setup that can be used for different meditation styles. Preparatory moments can be the same for all meditation styles to generate the baseline for an individual. Disentanglement and Mindful moments require different models based on the meditation style to navigate a practitioner to start.

1) Focused Attention Meditation: Meditators practice maintaining their deliberate, focused attention on a particular target item, such as while concentrating on their breathing, they silently recite a sound or set of sounds (mantra). [33]. The presence of a focused object allows meditators to direct their attention away from distractions and to effortlessly separate their attention from them. This purposefully focused attention meditation is linked to the brain's attention networks. Due to the highly concentrative nature of FAM, it creates a narrower attentional focus [34].

a) Audio: Several audio available online are used for focused attention mediation [35]. Sound calmness, clarity, and noise intensity can modulate based on the mind-wandering and

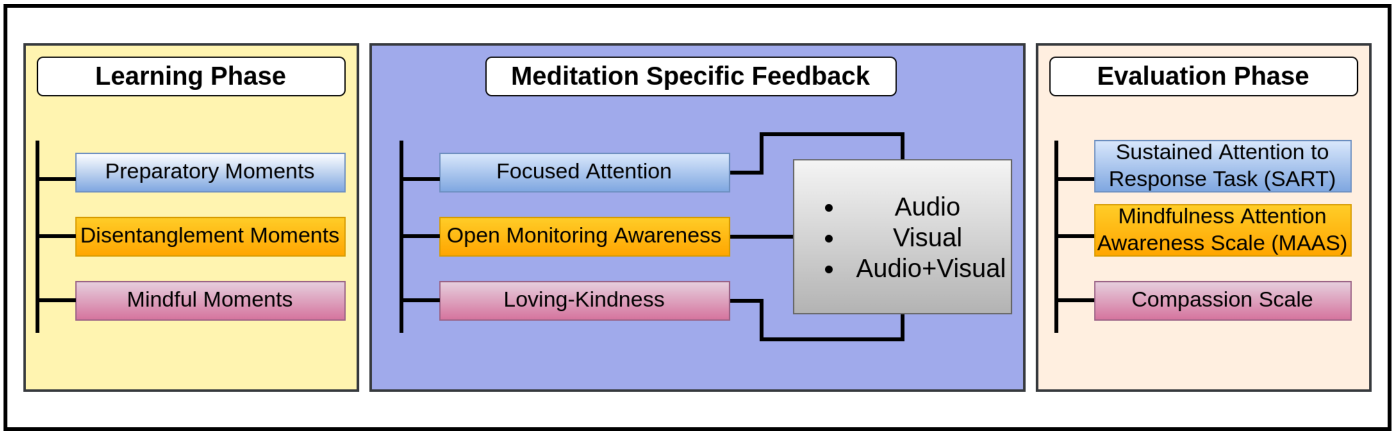

Fig. 2. Proposed framework includes learning phase, meditation specific feedback, and evaluation phase

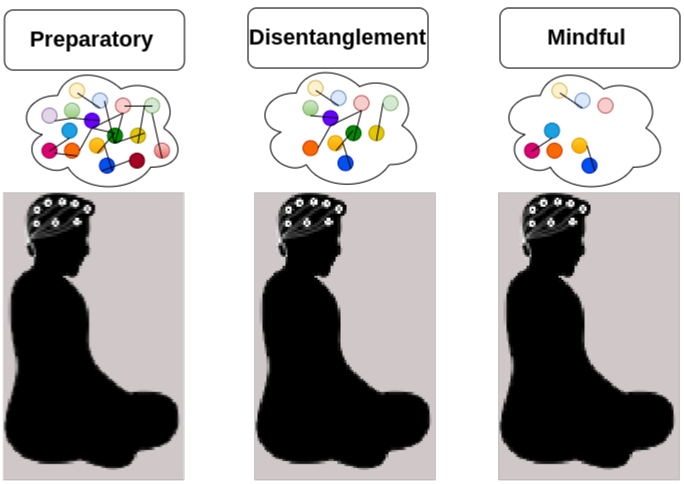

Fig. 3. Preparatory Moments is to record the baseline and initial stage. Disentanglement Moments is to focus on the meditation objective and settling down. Mindful Moments is to experience the meditative states.

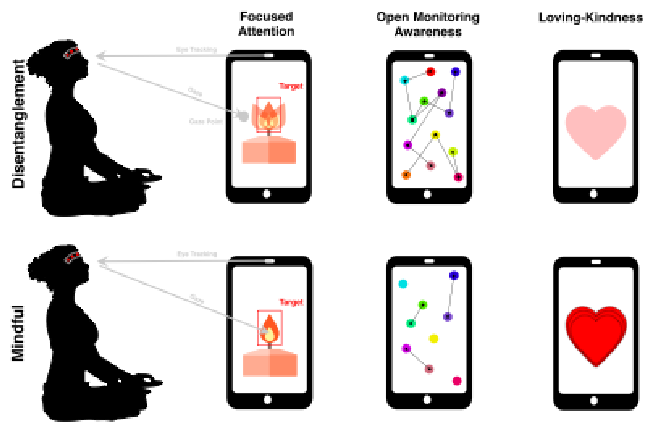

Fig. 4. [Left] Focused Attention Meditation: The individual starts focusing on the candle flame in disentanglement moments and gradually reaches a mindful state where the candle flame is concentrated in a particular region. [Middle] Open Monitoring Awareness: Thoughts are arising and judgment illustrate here as a connection, gradually judgment is reduced with the frequency of thoughts and finally reaches a mindful state. [Right] An individual enhances positive emotions by looking at loving (or someone he loves) images and gradually reaching a mindful loving state.

attention score obtained from the model based on real-time EEG data.

b) Visual: Animation can describe the change in motion as per the user's brain signals and gaze data. For instance, a candle flame is sharply illuminated if the attention is focused and spread if the distraction is detected, as shown in Fig. 4. Eye tracking can trace a user's gaze region, and mind-wandering can be detected.

c) Audio+Visual: Both Audio and Visual would synchronize and provide better-personalized feedback to the user.

Challenge: Training attentional components are the sincere objective of this style. The complex part of this feedback to identify the mind wandering and focused attention correlates to providing the correct feedback. The mind-wandering events can be further classified based on the brain signals on a scale of 1 to 3. Several studies have been published in this direction to identify the mind wandering states using EEG and gaze data [36], [37] and providing focused attention feedback [38].

2) Open Monitoring Awareness: Mentally examines each body part one by one, experiences the sensations of all of these body parts, and transfers one's attention in a repeating pattern from the top of the head to the ends point, paying attention to bodily sensations, feelings, and thoughts. The fundamental goal is to keep the attention moving and to monitor the sensations one has with non-reactive and non-judgmental awareness objectively, and with equanimity [33]. Here, one gradually diminishes purposeful concentrated attention while avoiding distractions without a defined object [39]. By accepting and recognizing any experiences that may arise during meditation, OMM creates a broader attentional focus. [34].

a) Audio: Several meditation based applications such as apps give detailed instructions on how to pay attention to physiological sensations, feelings, and ideas, which are not distractions but rather contents. For instance, audio is presented to observe bodily sensations, and volume can be modulated based on the user's gaze and EEG data.

b) Visual: Animation can show the intensity of thoughts and judgment in the intial moments and later reduces as the individual gains experience and reaches mindful moments as shown in Fig 4.

c) Audio+Visual: More heightened experience can be generated by combining audio and visual with synchronization.

Challenge: Individuals would focus on their metacognitive awareness. Compared to focused attention, it involves observation without judgment. Hence complexity is how to differentiate the level of judgment and provide the feedback based on that to progress towards minimum judgement.

3) Loving-Kindness: Meditation strives to cultivate unconditional kindness for the wellbeing and happiness of oneself and others. Meditators begin by establishing love and compassion for oneself, then progressively extend this love to equally "unlikable" persons (e.g, from self to friend, stranger, and all other beings). Positive associations, such as pro-social or compassionate, empathetic behaviour, are intended to replace any potentially negative interactions. Loving-kindness Meditation is supposed to improve one's ability to withstand, rather than avoid, uncomfortable ideas, pictures, and feelings, as well as to combat shame, guilt, and emotional numbness [34]. It has been proposed that practicing loving-kindness meditation (LKM) is an excellent way to promote pleasant and joyful emotions. [40].

a) Audio: It fills someone with warmth and love. Receiving loving-kindness, offering loving-kindness to loved ones, extending loving-kindness to neutral individuals, and spreading loving-kindness to all living beings are the main themes of the audio content. For instance, "Keeping your eyes closed, think of a person close to you who loves you very much" [41].

b) Visual: Compassion visuals can be shown that cultivate unconditional kind attitudes toward oneself and others. [42]. Several animations are available online that can be leveraged and modified based on the feedback. If there is a distraction during the practice, visuals can be shaded or blurred as shown in Fig. 4.

c) Audio+Visual: The combination may generate a feeling of relaxation and a powerful medium to experience.

Challenge: This involves an understanding of emotional components. A recent study found that focused and loving-kindness meditation produce different brain activity. [43].

C. Evaluation Phase

After some sessions, a practitioner can take some tests to check his performance. There are several scales respective to each task. Sustained Attention to Response Task (SART) is a extensively employed scale to evaluate mind-wandering. It is a popular sustained attention task linked to mind wandering in everyday life and mind-wandering measured during focused breathing exercises, involving self-caught task-unrelated thought. During the SART performance, mindfulness reduces mind wandering and enhances sustained concentration. [44]. The Mindfulness Attention Awareness Scale (MAAS) is also widely used to assess awareness. It evaluates individual variations in the incidence of mindful states across various periods. Its main assessment is based on the presence or lack of attention in the current scenario despite other features such as acceptance, trust, empathy, gratitude, etc, which are linked with the mindfulness [45]. Multiple factors are being assessed in the compassion scale, such as positive qualities toward self, positive qualities toward others, negative qualities toward self, and negative qualities toward others. [46].

IV. Discussion and Conclusion

Non-invasive neurotechnologies offer a new and scalable method for monitoring and modulating brain activity [17]. Nearly,85% of the global brain-computer interface (BCI) market by 2027 is predicted to hit $3.85 billion by 2027 [47]. We propose to build a Mindfulness Kit, and this work is the initial framework on which several components can be connected to build a prototype. Our previous studies have shown evidence of neural signatures associated with expert meditative states using machine, and deep learning techniques [9], [13], [14], [48]. These neural signatures may be utilized to train a naive practitioner to reach a mindful state. Neurofeedback techniques may make meditation easy, encouraging meditation practices to be more accessible to a broader audience. EEG feedback system for meditation has made a significant space in the industry, and several companies are designing products for consumers to experience meditative states. This research proposes a framework to create a system based on mediation style.

V. Limitation

The feasibility of some proposed modules for real-time settings can be validated and updated with the growing research. However, this research presents a significant research direction in human wellness and proposes developing a Mindfulness Kit for everyone.

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