EEGlass: An EEG-Eyeware Prototype for Ubiquitous Brain-Computer Interaction

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ABSTRACT

Contemporary Head-Mounted Displays (HMDs) are progressively becoming socially acceptable by approaching the size and design of normal eyewear. Apart from the exciting interaction design prospects, HMDs bear significant potential in hosting an array of physiological sensors very adjacent to the human skull. As a proof of concept, we illustrate EEGlass, an early wearable prototype comprised of plastic eyewear frames for approximating the form factor of a modern HMD. EEGlass is equipped with an OpenBCI board and a set of EEG electrodes at the contact points with the skull for unobtrusively collecting data related to the activity of the human brain. We tested our prototype with 1 participant performing cognitive and sensorimotor tasks while wearing an established Electroencephalography (EEG) device for obtaining a baseline. Our preliminary results showcase that EEGlass is capable of accurately capturing resting state, detect motor-action and Electrooculographic (EOG) artifacts. Further experimentation is required, but our early trials with EEGlass are promising in that HMDs could serve as a springboard for moving EEG outside of the lab and in our everyday life, facilitating the design of neuroadaptive systems.

CCS CONCEPTS

• **Hardware → Neural systems**.

KEYWORDS

Head-Mounted Displays, Electroencephalography, Brain-Computer Interfaces, Neuroadaptive Systems

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1 STATE OF THE ART

In the year 2022, over 80 million Head-Mounted Display (HMD) units are expected to ship, up from over 34 million units estimated to be sold in 2019[1]. This predicted HMD proliferation is propelled by recent advances in optics and hardware miniaturization, rendering eyewear the next frontier for Wearable and Ubiquitous Computing (e.g., Google Glass Enterprise Edition[2], Microsoft HoloLens 2[3], MagicLeap One[4], Focals by North[5] and Vuzix Blade[6]). Undoubtedly, an HMD uptake will actualize the vision of Augmented Reality (AR), disrupting the way we consume information and execute our daily chores [3]. From revisiting the groceries list to navigating to our destination, a plethora of daily tasks will be reshaped by AR and the unique form factor of HMDs. Except for the immense opportunities in interaction design, the HMD form factor promises an unprecedented contact potential with the human skull: the shell of our brain where the higher cognitive and perceptual processes reside.

Evidently, this "skull-contact" potential that eyewear bears could not go unnoticed. Various commercial eyewear products claim to utilize EEG (or EOG – electrooculography) and the contact points with the skull to provide so-called "neurofeedback". For example, Narbis sunglasses[7] utilize three electrodes, two at the back of the temples of the device touching the left and right mastoids, and one at the tip of a protruding arm that touches the top of the skull, for tracking concentration. When concentration is low, the Narbis electrochromatic lenses start darkening for inviting the user to focus more. Lowdown Focus by Smith[8] employs a more socially acceptable design equipping a typical pair of sunglasses with silicon electrodes at the edges of the temples that touch the left and right mastoids. A companion mobile application connects to the Lowdown Focus sunglasses for collecting the readings so that one can track and increase one's concentration levels. JINS

[1] https://www.gartner.com/en/newsroom/press-releases/2018-11-29-gartner-says-worldwide-wearable-device-sales-to-grow-
[2] https://www.google.com/glass/start/
[3] https://www.microsoft.com/en-us/hololens
[4] https://www.magicleap.com/magic-leap-one
[5] https://www.bynorth.com
[6] https://www.vuzix.com/products/blade-smart-glasses
[7] http://narbis.com/company/
[8] https://www.smithoptics.com/us/lowdownfocus

Figure 1: The EEGlass prototype worn by a user.

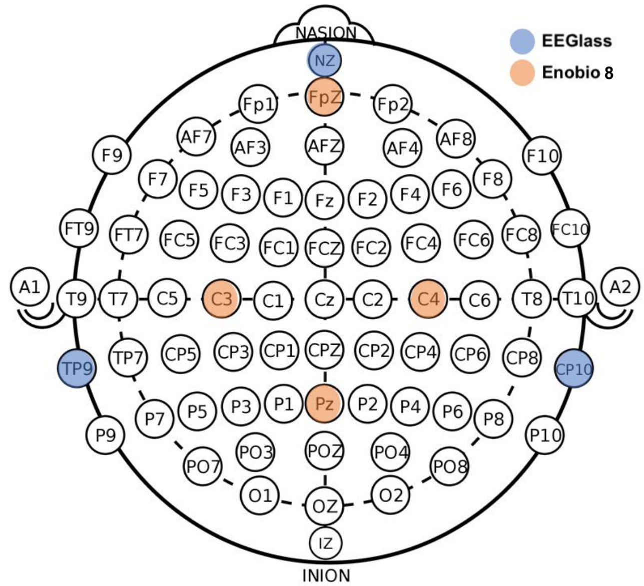


Figure 2: The 10-10 system of electrode placement topology for the EEGlass and Enobio 8.

MEME[9] is perhaps the most prominent eyewear that employs near-skull contact for providing neurofeedback. JINS MEME utilizes two electrodes embedded in the bridge of the eyewear that touch the nasal bone to detect concentration levels by measuring the duration and the number of eye blinks via EOG [20]. More recently, a US patent was published about the design of an eyewear frame that features a flexible protrusion for holding the EEG electrodes in contact with the skull in different positions [5]. Beyond the strong commercialization interest, the combination of eyewear with EEG yields interesting niche applications in the domain of health research and Human-Computer Interaction (HCI). e-Glass is an EEG-enabled eyewear that employs an OpenBCI board and a set of electrodes across the inner side of the frame for detecting epileptic seizures [19]. PhysioHMD prototype adopts a bulky "mask" design that encases a portion of the face for hosting a wide range of physiological sensors, including EEG electrodes, capturing also facial expressions [2]. PhysioHMD is intended as a platform that informs the design of AR and Virtual Reality (VR) experiences.

On one hand, commercial approaches that combine modern eyewear with EEG (and EOG) are in general socially acceptable, but also rather limited in providing high-level information about brain activity (e.g., daily concentration levels), typically via a dedicated mobile application. Moreover, commercial "neurofeedback" products are considered "black-box" systems that utilize proprietary hardware and software. On the other hand, experimental EEG-eyewear prototypes produce fine-grained information about brain activity, while utilizing open hardware and software solutions. However, such prototypes are by default too dorky to wear outside a research lab, and cumbersome to use for extended periods of time. The EEGlass prototype attempts to fuse the social acceptability and increased "wearability" of commercial EEG-eyewear with the high information granularity and openness of experimental EEG-eyewear (see Figure 1). The outcomes of such a successful fusion remain tentative but can potentially nurture existing and envisioned cognitive systems [13], democratize EEG, and eventually pave the way for touch-less input.

2 BACKGROUND

The human brain is an electrochemical system that generates a combination of dynamic biosignals or action potentials. EEG is the most common brain signal acquisition technique established almost a century ago [1]. Non-invasive EEG utilizes scalp-contact electrodes for capturing the combined electrical activity of populations of excitable cells known as neurons. When neurons activate, they produce electromagnetic fields of discrete potential patterns, distinguished by different wave oscillations in the frequency domain. These patterns are ascribed to different states of mental activity and are identified by the wave oscillations they cause in the frequency domain, known as EEG bands or rhythms [4]. EEG rhythms are divided into different frequency ranges including Delta (1–4 Hz), Theta (4–8 Hz), Alpha (8–13 Hz), Beta (13–30 Hz) and Gamma (25–90 Hz) [11], and each rhythm or combination of rhythmic activity is linked to different mental states. For example, rhythms in the Alpha and Beta frequency bands are functionally related to major sensorimotor systems, which activate primarily through motor preparation or execution [6]. Alpha and Theta oscillations are known to reflect cognitive and memory performance [9], and Theta was shown by early EEG studies to be closely connected to problem-solving, perceptual processing and learning [18]. Delta rhythm is related to concentration, attention and internal processing [8], whereas Gamma has been linked to consciousness and sense of self, and can be volitionally modulated during meditation [10].

[9] https://jins-meme.com/en/

Last accessed on July 3, 2019.

Figure 3: The EEGlass electrode contact points and the respective OpenBCI channels.

Interpreting cognitive states or motor intentions from different EEG rhythms is a complex process and is impossible to associate a single frequency range, or cortical location, to a brain function.

Nowadays, measuring oscillatory brain activity with EEG is utilized for linking the human brain with computers via Brain-Computer Interfaces (BCIs). BCIs have been successfully utilized in the medical domain where BCIs enable amputees to gain control over prosthetic limbs [15]. Other BCI application areas include monitoring user's cognitive states (e.g., attention levels and workload), gaming and rehabilitation. Thus, BCIs and wearable technologies such as HMDs, offer a unique opportunity to measure user needs over time and in real-life settings, informing how critical software aspects (e.g., interface) should respond or adapt. The potential of EEGlass in monitoring surreptitiously and in real-time user's physiological and cognitive states, renders it an ideal BCI for facilitating interaction with neuroadaptive systems.

3 EEGLASS PROTOTYPE

The EEGlass prototype is comprised of plastic eyewear frames that can be fitted with a Google Glass HMD. We opted for this type of eyewear for: (1) low cost, (2) availability, (3) good fitting and (4) modern HMD resemblance. In fact, the selected eyewear frames follow the trend in the field of HMDs: hardware miniaturization and social acceptability [12]. The EEG system that we embedded in the frames is Cyton Biosensing Board by OpenBCI (OpenBCI, NY, USA). OpenBCI is a popular and affordable open hardware and software platform for the collection and analysis of biosignals such as EEG, EMG (Electromyography), ECG (Electrocardiography) and others, inspired by the grassroots movement of DIY ("Do It Yourself") [21]. The Cyton board encompasses 8 biopotential input channels (for hosting up to 8 electrodes), a 3-axes accelerometer, local storage, wireless communication modules, while being fully programmable and Arduino compatible. Evidently, the EEGlass electrode topology is restricted by the eyewear form factor and at the contact points with the skull. Thus, EEGlass utilizes 3 electrodes (plus 2 for reference and ground) based on the 10-10 system (see Figure 2) for measuring brain activity: 1 electrode placed inwards at the top of the eyewear bridge touching the skull at glabella, and 2 more electrodes at the inner side of the eyewear temples, touching the left and right mastoids, behind the left and right ears,

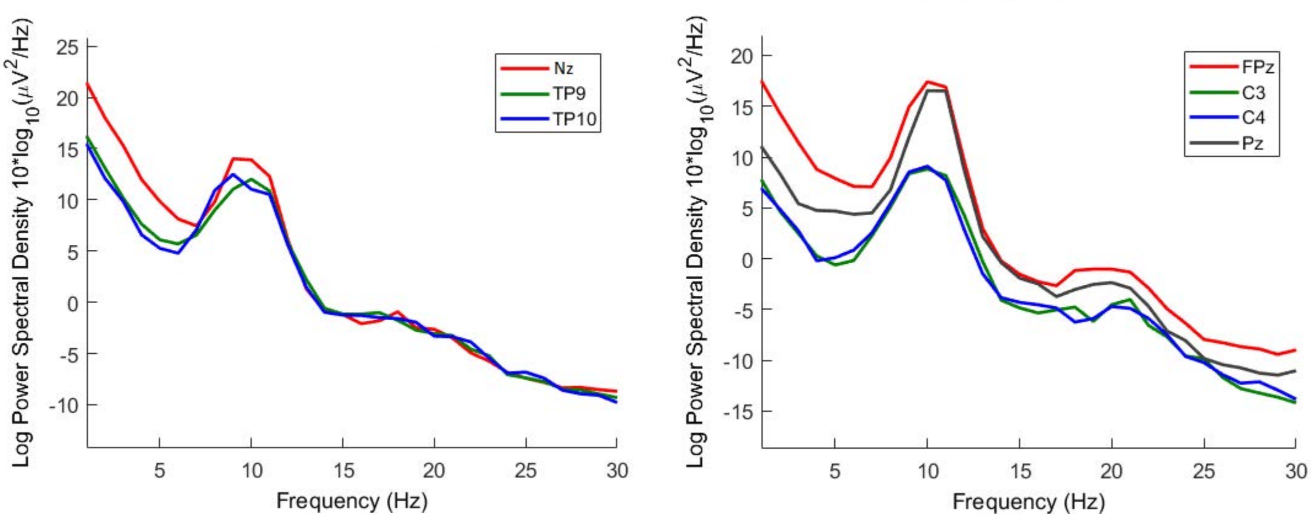
Figure 4: A user performing a motor task while wearing both EEGlass and Enobio 8 EEG systems.

respectively (see Figure 3). The reference and ground electrodes are placed at the inner part of the eyewear bridge, touching the left and right sides of the nasal bone, respectively (see Figure 3).

4 FIRST TRIALS AND EARLY RESULTS

In this work, we explore if the low spatial resolution of a "skull-peripheral" electrode topology, imposed by the form factor of a modern HMD, can approximate the accuracy of a typical electrode topology utilized in EEG studies. To this end, we used Enobio 8 (Neuroelectrics, Barcelona, Spain) EEG system for forming a baseline. Enobio 8 is a wireless, 8-channel, EEG system with a 3-axes accelerometer for the recording and visualization of 24-bit EEG data at 500 Hz. The spatial distribution of electrodes for our trials followed the 10-10 system configuration, with electrodes placed over the frontal area (Fpz), central (C3, C4), and parietal (Pz) (see Figure 2). The electrodes were referenced and grounded to the right ear lobe, and the electrode impedance was kept at $< 20\,k\Omega$. Both the Enobio 8 and the OpenBCI (embedded in the EEGlass) EEG systems were connected via Bluetooth to a dedicated desktop computer for raw signal acquisition and processing.

The EEG acquisition session began with a 4-minute period for acquiring resting state data, and the motor-action session following next. The resting state data was acquired during alternating 1-minute periods with eyes open and eyes closed. The subject was instructed to remain silent while either fixating his eye-gaze on a white cross displayed on a computer screen, or when having his eyes closed. In the motor-action session, we employed the Graz-BCI paradigm [16] to display a random sequence of directional left and right arrows on a computer screen (see Figure 4). When an arrow appeared, the user responded to the stimulus by performing a motor-action with the corresponding hand. The motor-action session was configured to acquire data in 24 blocks (epochs) per class (left and right hand arrow).



(a) EEGlass resting state. **(b) Enobio 8 resting state.**

Figure 5: Resting states for EEGlass and Enobio 8. Both EEG systems detect a clear Alpha rhythm peak at 8-12 Hz.

For both systems, we used the OpenVibe acquisition servers for simultaneous EEG signal acquisition [17]. Next, we used the OpenVibe designer for obtaining the raw EEG streams from both servers and synchronizing them with the stimuli, before storing them in a *.gdf* file. We processed the acquired EEG signals in MATLAB® (The MathWorks, MA, USA) with the EEGLAB toolbox [7]: after importing the data and the channel information, we applied a high-pass filter at 1 Hz to remove the "baseline drift" followed by line-noise and harmonics removal at 50 Hz. Then, we used Welch's method [22] for Power Spectral Density (PSD) of the power spectrum to compute the average spectral power across the following frequency bands during resting state: Delta (1–4 Hz), Theta (4–7 Hz), Alpha (8–12 Hz), and Beta (12–30 Hz). The event-related synchronization/desynchronization (ERS/ERD) was extracted following the standard ERS/ERD method [14] across the Alpha band power (8–12 Hz) and the Beta band power (12–30 Hz) over C3 and C4 electrode locations for the Enobio 8 system, and TP9, TP10 for the OpenBCI, respectively. We calculated the ERD by using the following formula:

$$ERD = \frac{(Power_{MotorActivity} - Power_{Baseline})}{Power_{Baseline}} * 100 \qquad (1)$$

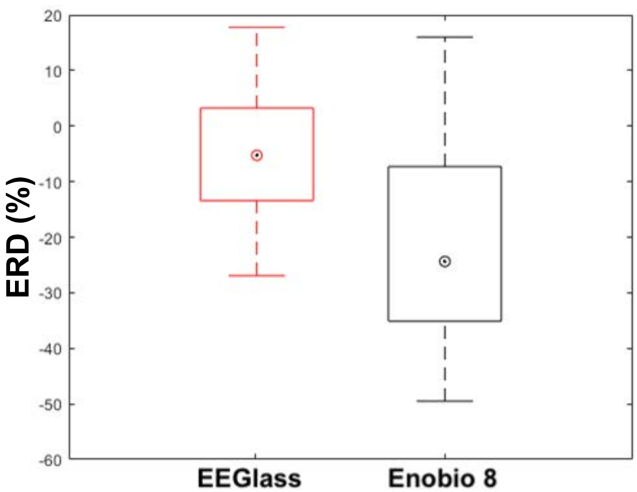
Early results from comparing EEG signals acquired via EEGlass with Enobio 8 indicate that EEGlass captures very closely the band power of Enobio 8, but also the the decrease of oscillatory activity (ERD) during the motor-action, as we anticipated. Figure 5 shows that despite the fundamentally different electrode topology of EEGlass, both EEGlass and Enobio detect a clear Alpha peak (8–12 Hz) in the electrical activity of the brain during resting state. Table 1 summarizes the recorded EEG rhythms during resting state for both EEGlass and Enobio 8 EEG systems. For investigating if brain activity linked to motor-action differed substantially between the two EEG systems, we compared the average ERD between lateral electrodes for both systems: $\Delta(TP9, C3)$ for right-hand, and $\Delta(CP10, C4)$ for left-hand movement. Dependent samples t-tests displayed significant differences in the average ERD between both pairs of lateral electrodes ($t_{TP9|C3}(199) = 10.214, p < .001$ and $t_{CP10|C4}(199), p < .001$), as shown in Figure 6 and summarized in Table 2. This indicates that the captured brain activity related to upper limb motor-action differed significantly between the EEGlass and Enobio 8 EEG systems. Moreover, Figure 7 showcases that EEGlass was able to detect basic EOG activity related to eye movement in 4 primary directions: up, down, left and right. Although the current electrode setup can capture eye-movement with only 1 degree-of-freedom (DoF), it can also detect saccadic eye movement and eye blinks.

Table 1: Resting state and EEG rhythms in $\mu V^2/Hz$ recorded by EEGlass and Enobio 8 EEG systems.

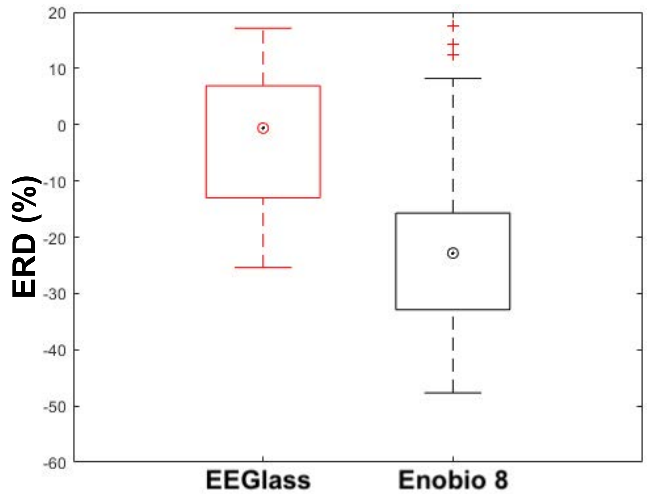
System	Delta	Theta	Alpha	Beta
EEGlass	21.279	4.775	12.992	0.431
Enobio 8	4.984	2.196	13.397	0.2993

Table 2: Average desynchronization (% ERD) between 8–24 Hz per electrode and hand for both EEGlass and Enobio 8 EEG systems.

	EEGlass		Enobio 8	
Electrode	TP9	TP10	C3	C4
Movement	Right	Left	Right	Left
Mean	-5.058	-3.065	-20.272	-18.899
SD	11.6383	12.273	19.048	22.47



(a) Left hand ERD as captured by CP10 (EEGlass) and C4 (Enobio 8) electrodes.



(b) Right hand ERD as captured by TP9 (EEGlass) and C3 (Enobio 8) electrodes.

Figure 6: Average motor-action (ERD) for lateral electrode pairs of both EEGlass and Enobio 8 EEG Systems. Significant differences ($p < .001$) were found between both electrode pairs for both right and left hand motor-action.

5 DISCUSSION AND FUTURE WORK

Our preliminary results serve as a proof of concept for piggybacking EEG on eyewear and HMDs, yet in a cost-effective, unobtrusive and socially acceptable fashion. Trials with 1 participant indicate that the EEGlass is capable of capturing brain activity manifested in two modes of resting state: (a) eyes open and focused on a target, and (b) eyes closed. In fact, brain activity recorded during resting state with EEGlass demonstrates similar variations in frequency and amplitude to when recorded with an established EEG system such as Enobio 8. However, recorded brain activity linked to upper limb motor-action and captured with EEGlass, displayed significant differences when compared to that captured with Enobio 8, as anticipated due to the localized motor activity of the sensorimotor cortices under C3, C4 electrodes. Yet, EEGlass managed to capture ERD from its TP9 and TP10 electrodes, though with less power than Enobio 8 due to the low spatial resolution of the EEG signals on the scalp, relying on signal propagation to reach the remotely located EEGlass electrodes. Moreover, EEGlass was able to detect subtle eye movements in 4 basic directions, displaying an eye-tracking potential particularly useful for navigating in heads-up interfaces.

Undoubtedly, low sample size (N=1) and stationary experimental settings are significant limitations that we will address in followup studies. However, human skull and brain anatomy is universally homogeneous, and the eyewear/HMD form factor ensures a rather stable electrode contact, only somewhat influenced by movement. In future iterations, we will utilize prominent machine learning techniques for training algorithms to match input from EEGlass to that of established EEG systems, and test our prototype in user studies with actual HMDs. We believe a merger between EEG and HMDs bears an unprecedented potential to revolutionize human-machine interaction, facilitating touch-less input and greatly increasing human-machine communication throughput.

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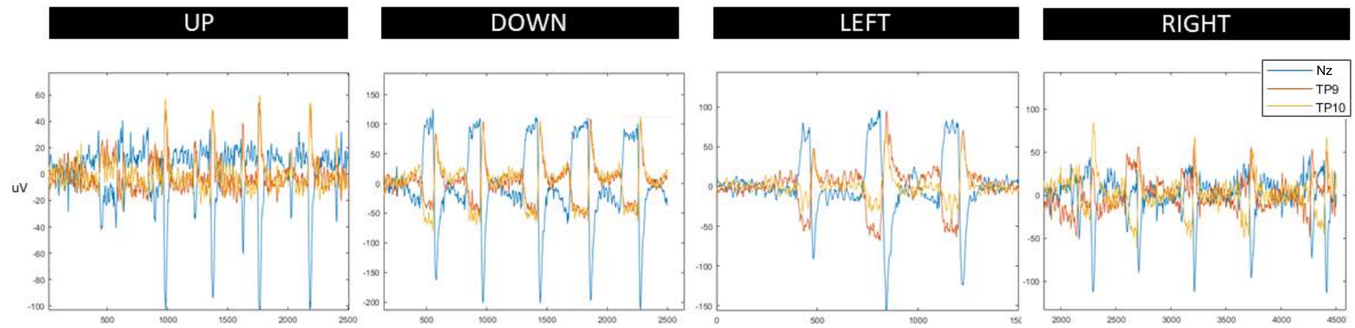

Figure 7: Electrooculographic (EOG) activity ($\mu V/ms$) recorded by EEGlass and linked to eye movement in 4 basic directions.

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