An Analysis of Electrooculography (EOG) Acquisition Systems for Use in Assessment of Mild Traumatic Brain Injury

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Introduction

The following deliverable will serve as an overview of the work I completed this spring, as well as a reference for myself and others interested in the same line of research.

My work this semester continued my efforts last semester towards designing a circuit to accurately measure electrooculography (EOG) signals for eventual use in a mobile eye-tracking system. As it stands, our Bass Connections team uses an Eyelink Infrared System to track the gaze of study participants across a series of eye-tracking test [1]. The Eyelink system offers an accurate and generally reliable way to measure participants' gaze, however, the Eyelink system retains several drawbacks as opposed to EOG technology. Foremost, building an EOG eye-tracking system would likely be significantly less expensive than the Eyelink system, which costs nearly $10,000. Further, an EOG system has the potential to be extremely portable when compared to the Eyelink system. Our current Eyelink setup involves the Eyelink Infrared Camera and a desktop monitor affixed to an aluminum frame contained within a 6' by 6' black tent to eliminate external visual distractions from the test subject. We plan for our EOG system to be contained within a wearable headset comparable to modern virtual reality headsets. This level of portability would allow for the rapid deployment and use of an eye-tracking system, such as on the side-lines of an ongoing sporting event. Finally, an EOG-headset device may be a more comfortable eye-tracking alternative when compared to our current Eyelink system. Our current testing procedure requires study participants to fix their head on a chinrest for approximately 15 minutes to stabilize the position of their eyes with respect to the infrared camera. Packaging EOG electrodes within a mobile headset may thus allow the study participant greater freedom of movement in the testing process.

My work this semester concentrated on physically implementing the EOG acquisition circuit designed over the course of last semester. Over this process, I built upon the work of past Bass teams that had designed their own EOG-acquisition circuits. Most of the circuit I worked on was modelled according to a proto-board circuit I reverse-engineered last semester. In addition to ordering the circuit components, breadboarding, and testing, I also engaged in a high degree of personal study to understand the intricacies of the circuit. I gained a working understanding of instrumentation-amplification techniques for high-common mode signals (such as EEG, ECG, and EOG) which underpin the circuit I ultimately built. I believe I also developed a stronger knowledge of circuit prototyping in general, including the process of selecting parts to correct specifications, working with component data sheets, and constructing a larger circuit through individually testable modules.

Background

A concussion, or mild traumatic brain injury (mTBI), is a type of injury to the brain resulting from excessive biomechanical forces applied to the head. TBIs as a whole account for an average of 1.1 million annual emergency room visits in the United States. Concussions are the most common form of TBI, and estimates suggest mTBI to be at least 10 times as frequent as moderate or severe TBI [2-4]. Most concussions do not result in emergency-room visits, and there is an estimated 1.7-3.3 million concussion occurring each year due to sport and recreation activities alone [5]. Concussions often go unreported and the true number of concussion occurring each year may be much higher than this estimate [6]. Although often discussed in the context of sports related events, concussions may result from any sufficiently high blunt force or whiplash to the head, such as from a fall, car accident, or one's work environment [7].

The mechanical etiology of mTBIs is often complex and highly variable given the number of ways external forces may exert pressure on the brain [4]. There are two primary categories of forces which comprise most mTBI-inducing impacts: contact forces and inertial forces. Contact forces, concentrated forces at the impact site, are associated with localized skull fractures and focal brain injuries such as epidural hematoma. Injuries of this type most commonly present in severe TBI, and rarely occur with mTBI [8]. Inertial force/acceleration, defined by the loading experienced by the brain during impact, is thus responsible for most mTBI-related injury. Inertial forces consist of some combination of linear force and torque, which respectively cause linear and rotational motions of the brain. Substantial work has found an association with maximum linear force and loading experienced by the brain [9, 10]. Linear acceleration is also highly correlated with concussion likelihood [11]. However, the current scientific consensus has established that rotational acceleration is the primary source of injury in mTBI [4, 12]. The brain is particularly susceptible to shear forces caused by rotational acceleration [13]. Research has demonstrated the central influence of rotational acceleration on concussion severity, with one study demonstrating it is extremely difficult to induce unconsciousness on animal subjects via linear forces alone [14].

The brain's deformation under a traumatic load launches a "neurometabolic cascade" responsible for the cellular-level damage associated with a mTBI [15]. Upon initial impact, tears in the lipid membranes of brain cells cause the indiscriminate release of potassium ions and glutamate, as well as the rapid intake of sodium and calcium ions [16]. Extreme extracellular ion concentrations may then trigger further ion channels, cause a chain reaction and further increasing extracellular ion levels across the brain tissue [17]. Ionic pumps then go into overdrive as the brain attempts to restore normal ion levels and cellular homeostasis. These ion pumps require energy which brain cells acquire through hyperglycolysis, ultimately resulting in an oversupply of ADP and the depletion of the brain's energy reserves [18]. The brain thus enters a period of metabolic mismatch in which the demand for energy exceeds the supply. This altered metabolic state may last for up to 7-10 days and has been associated with cognitive dysfunction in animals [18]. The deformation of the brain may also affect the cellular structure of brain cells, impairing axon function and causing cytoskeletal damage [17]. mTBI has been further associated with many types of dysfunction, including deficits in neurotransmission, increased inflammation, and in the case of repeated head impact, potentially brain atrophy. [17] With time, studies have associated many of these cellular changes with specific symptoms of concussion. For instance, extreme ionic flux has been correlated with migraines, the brain's altered metabolic period has been associated with increased vulnerability to further impacts in the period following an mTBI, and impaired neurotransmission has been tied to cognitive dysfunction [15].

Concussions are associated with a set of acute and prolonged symptoms. In the short term, concussions may cause a wide variety of symptoms depending on the individual patient. Most individuals who experience a concussion develop some level of headache, difficulty concentrating, fatigue, and mental "fog" among other symptoms [19]. A smaller number of concussions are associated with more physically apparent symptoms including vomiting, visual problems, and balance problems [19]. Most individuals diagnosed with a concussion recover within 7 days and display no clinical deficits following this period [20] .

However, a growing body of literature has highlighted the potential long-term effects of concussions. Chronic traumatic encephalopathy (CTE) is a degenerative brain disease associated with repeated mild traumatic brain injury [21]. Individuals often present with CTE long after their athletic careers, and a set of recently confirmed cases among high-profile athletes has spurred attention towards the disease [22, 23]. CTE has a complex disease pathology currently poorly understood by the scientific community. Current theories accredit the cognitive decline present in CTE to factors including intracellular metabolic dysfunction, cumulative cell death, and the accumulation of toxic proteins in brain tissue [17]. CTE may only be diagnosed post-mortem, and it is difficult to predict which athletes will ultimately suffer from the condition [21]. A single season of football has been linked to alterations in brain white matter [24], and even heading a soccer ball is associated with white matter microstructural and cognitive abnormalities [25]. Nevertheless, most individuals who participate in contact sports do not develop CTE. It is thus of great importance to determine if there exists a threshold or a precise means of assessing an individual's risk of developing long-term deficits from head impact.

As researchers have devoted increased attention towards the potential long-term ramifications of repeated head injury, recent years have seen an increase in awareness towards the risks of mTBI. Especially in sports settings, concussions have occasionally been known to be disregarded as a minor injury, sometimes one which an athlete may "walk-off" and immediately return to play [26-28]. As research has demonstrated increasingly serious ramifications of concussions, such as the potential for CTE, this attitude has shifted considerably over the past several decades [26]. Now, most professional, and often amateur, sports organizations have implemented formal policies to address concussions and regulate an athlete's return to their sport [29-31].

Given the wide-reaching and potentially devastating long-term effects of repeated sports-related concussion, it is important to develop strong diagnostic tools to determine the extent of each injury. To an outside observer, a concussion may often appear to be difficult to discern. Those concussed often present with a wide range of symptoms, many of which rely on self-reported scores to determine relative severity [27]. Further, almost all structural and functional deficits take place at the cellular level [32]. Barring a small minority of concussions (i.e. those that present with subdural hematoma), there are often no physically measurable signs of injury, even when analyzed using advanced imaging techniques [7]. As such, most clinicians and athletic trainers rely on a series of tests such as post-concussive symptom checklists and neurocognitive assessments to gauge concussion recovery and severity. Symptom evaluations have been found to be an effective predictor of concussion likelihood, with one study reporting that symptoms evaluation sheets may identify up to 90% of concussed athletes[27, 33]. Nevertheless, symptoms evaluations depend upon the full cooperation of the patient, and concussed athletes have often been reported to exaggerate baseline symptoms or play down post-concussion symptoms to accelerate their return to play [34]. Even if effective towards initial diagnosis, symptom evaluation sheets often fail to precisely quantify an athlete's recovery, as symptoms may vary on a day-to-day basis [27]. Further, without the aid of advanced imaging techniques, no concussion assessment may determine whether the brain has returned to typical metabolic activity. Even without the presence of clinical concussion symptoms, the brain may exist in a state of heightened vulnerability until it reaches full functional recovery [35].

Pending further research, imaging techniques such as functional magnetic resonance imaging (fMRI) or diffusion tensor imaging (DTI) may offer an objective way to gauge concussion severity and recovery. However, their high cost and limited accessibility may inhibit their regular use for concussion diagnosis [27]. Much research has also investigated the use of certain biomarkers present following brain injury for use in concussion diagnosis. One study achieved a concussion-prediction AUC of 0.68 by measuring blood glial fibrillary acidic protein (GFAP) levels in a set of concussed and non-concussed individuals [36].

The most widely used concussion diagnostic tools today thus retain a high degree of subjectivity. As such, the application of better objective diagnostic tools for concussion is of great interest to the research community. At the moment, there remains no single tool to effectively determine the exact time at which an athlete is safe to return to play [37].

A large body of work has attempted to determine concussion risk profiles through the biomechanical analysis of head impacts. There currently exist a wide variety of devices that record the acceleration and speed of an athlete's head during practice and gameplay [5]. Many studies have attempted to relate cumulative head-impact exposure or the qualities of specific impact events to concussion likelihood and severity [11, 38, 39]. One such study developed a risk likelihood curve according to rotational head acceleration, finding that a peak rotational acceleration of about 7000 rad/s^2 is associated with a 90% risk of concussion [11]. However, the same study found that concussive impacts display a wide range of rotational accelerations, and the range for concussive impacts overlaps considerably with non-concussive impacts. This fact would limit the statistical specificity of a concussion-predictor relying on this data alone. Another study conducted a statistical analysis using the HITS dataset, a compilation of the linear and rotational acceleration profiles across over 63,000 head impacts as measured with a Head Impact Telemetry (HIT) system [39]. Their model displayed a high degree of both selectivity and specificity, achieving an AUC score of 0.981. However, it is worth noting the HITs dataset is dependent upon both the accurate labelling of concussive vs non-concussive impacts, as well as the accurate collection of acceleration data. For instance one study has found that the Head Impact Telemetry System is prone to a high degree of error, meaning the HIT dataset is not a perfect representation of true impact profiles [40]. The use of biomechanical analyses may nevertheless provide a helpful diagnostic tool, yet such analysis is dependent upon the athlete wearing often expensive head-impact detection devices.

There exists much research demonstrating the effectiveness of eye-tracking towards the evaluation of mild-traumatic brain injury [37]. Oculomotor deficits are visible in as many as 90% of concussed individuals [41]. Although the motion of the human eye is determined by just three sets of oculomotor muscles, eye-movement entails many neural pathways extending to many parts of the brain. Accordingly, fine eye-movements are highly susceptible to brain injury and may serve as a reliable way to determine the existence/severity of concussion. Many studies have demonstrated measurable oculomotor deficits in concussed versus healthy populations using a variety of eye-tracking techniques [37]. However, oculomotor deficits have been found to be most prominent in the acute range following a concussion, within 30 days of the injury. Given the lack in quantity of directly comparable longitudinal eye-tracking studies, there is no consensus on the effectiveness of eye-tracking over longer periods than 30 days [37].

Electrooculography (EOG) is an eye-tracking technique which uses a set of electrodes placed around a person's eyes to determine eye movement. Metabolic activity within the human eye generates a slight negative charge in the retina [42]. Known as the corneal retinal potential, this charge creates a dipole across the long axis of the eye which is measurable by placing electrodes along strategic locations around the eyes. As the eye moves and the dipole shifts, electrodes can measure a difference in potential corresponding to various directions of movements, generally from 5 to 20 micro-Volts per degree of gaze shift [43]. A common EOG configuration is to place two electrodes above and below the eye to measure vertical movement and two electrodes to the right and left of an eye to measure horizontal movement [43, 44].

Infrared Reflection Oculography (IROG) is another prominent form of eye-tracking [45]. Infrared oculography involves shining invisible infrared light onto the face of the test subject. The sclera, or the outer white part of the eye, reflects more light than the pupil and iris. Infrared cameras may leverage this property to track the position of a subject's eyes as either more or less light is reflected depending on how much of the sclera versus the iris or pupil is visible to the camera. Most modern IROG systems may also identify structures of the eye such as the border between the iris and sclera to better determine subject gaze [45]. IR-based eye-tracking systems have been shown to be extremely accurate. The Eyelink 1000 system, for instance, tracks gaze to within 0.5 degrees [46], while the Dual-Purkinje-Image (DPI) gaze tracker has been shown to be accurate to within 0.1 degrees [47].

EOG displays several benefits over other eye tracking methods. Foremost, EOG systems are known to cost much less than eye-tracking methods involving camera setups. EOG electrodes are relatively inexpensive, and it does not require extensive circuitry or computing power to process an EOG signal. EOG systems generally have four input channels which, even if recording at high sample rates, do not require excessive storage or processing capabilities. This fact thus makes it extremely feasible to process EOG signals in real-time [48]. Many papers have demonstrated the use of EOG signal acquisition to measure eye movement at a high accuracy (within 1-2 degrees for horizontal movement [45]), often on par with established eye tracking methods, such as with an IR camera [49]. In fact, the accuracy of EOG systems is high enough to enable applications such as visual activity recognition and or as input to human computer interfaces [43, 50].

An active area of research is the development of mobile eye tracking (MET) systems. Today, most eye-trackers require subjects to either fix their head in place (as for most IROG systems) or at minimum to stay seated over the duration of the exam (given, for instance, the array of wires, power sources, or immobile sources of visual stimuli). The physical restraints imposed by eye-tracking systems are often uncomfortable to the test subject, yet they may also limit the ability to test individuals outside of a prepared lab setting. Certain fields of research require the subject to be mobile during the eye tracking process, thus necessitating the development of accurate MET devices [51]. For instance, marketing researchers may implement MET to determine how in-person (or online) customers allocate their visual attention towards advertisements or products [52, 53]. More general uses of MET hinge on the fact that the context of our surroundings/objects of engagement influence our visual perception [51]. Accordingly, MET is required to fully understand our eye movements in everyday situations. MET may also serve as a replacement for normal eye-tracking systems in situations in which it is inconvenient/impossible to conduct traditional eye-tracking a field setting.

There exist many MET systems in scientific literature as well as MET systems currently marketed for commercial use. I will review these systems in increasing subjective order of similarity to our project.

Several papers have demonstrated MET systems based on mobile smartphone cameras. Krafka et al. assembled a dataset of over 2.5 million images of people labeled by the position of their gaze [54]. Using the dataset, Kafka et al. trained a neural network which takes front-facing camera feed as input and achieved a gaze prediction error of 1.34 cm at a typical distance from one's eyes to their mobile device. Valliappan et al. trained a convolutional neural network which takes an image from a device's front-facing camera and outputs a gaze position with at most 0.75 cm of error at reading distance (corresponding to 0.6-1 degrees of error) [53].

The predominant type of MET system in use today, both for research purposes and otherwise, involves infrared (IR) tracking within a wearable headset. Kassner et al. outline an open-source eye-tracking platform named "Pupil" [55]. Pupil consists of an IR camera fixed to a lightweight headset as well as a software framework for mobile eye-tracking. Pupil is accurate to within 0.6 degrees of visual angle and displays a near-instantaneous processing speed [55]. Chugh et al. developed a camera-based eye tracking system for use in virtual reality applications, achieving an accuracy of 1.1 degrees through a convolutional neural network fed with camera input [56]. The paper also notes their system is 91% accurate at identifying corneal reflections resulting from the LED's necessary to illuminate the eyes. A company names Tobii AB developed an MET system called the "Tobii Pro Glasses 3" which implements IR tracking within a headset similar in form to a pair of eyeglasses [57]. Another company developed a virtual reality headset named "FOVE" equipped with IR eye-tracking. The headset reportedly tracks users' gaze to selectively render content in the VR video/image according to the user's field of view [58].

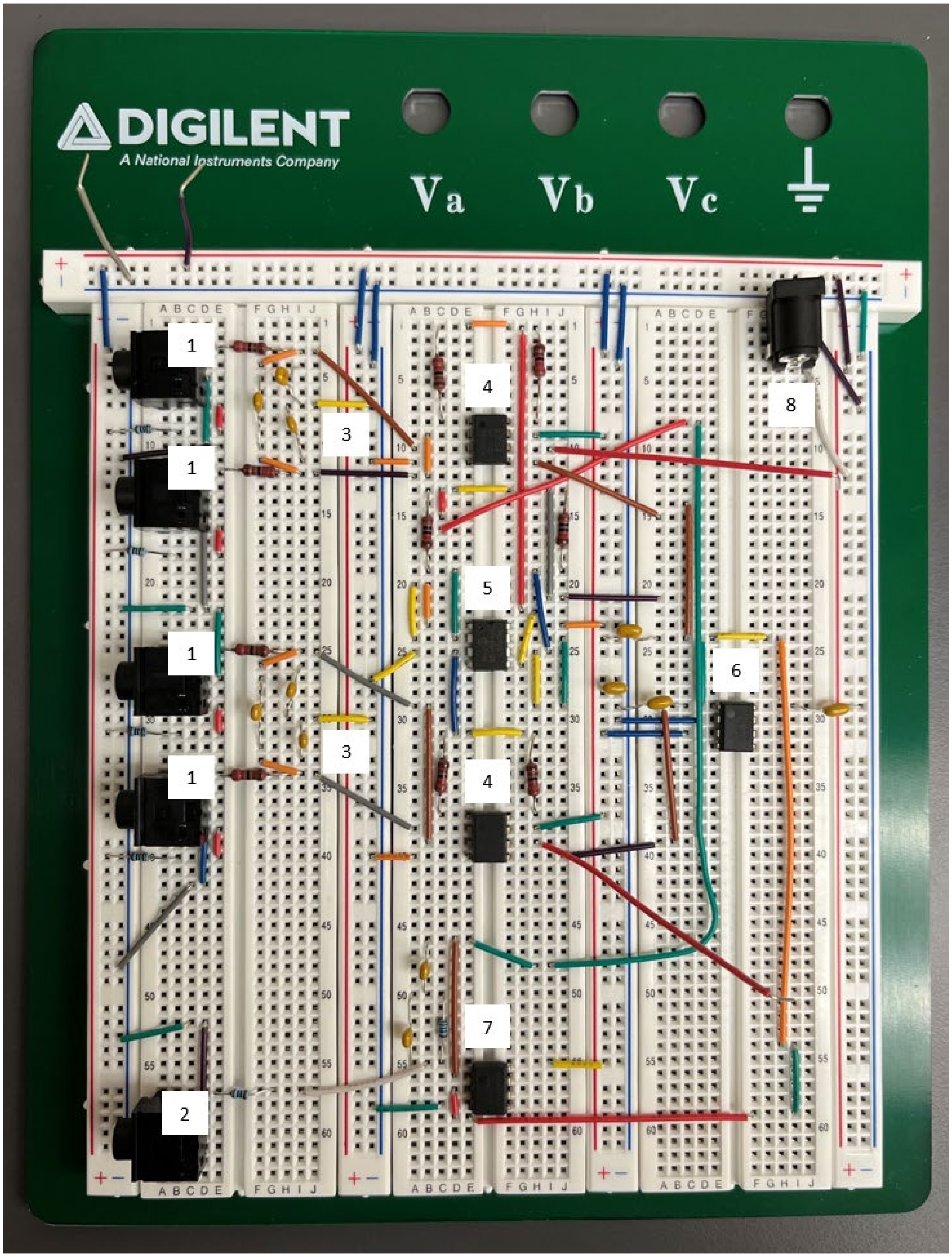
Finally, several papers have outlined MET systems based on EOG technology. Shimizu et al. developed a low-cost EOG-based eye-tracking system integrated within a Google Cardboard VR headset. [59]. Their system utilizes a pair of J!NS MEME smart glasses which possess a pair of electrodes within the nose bridge to measure ocular potential [60]. Their paper does however note that their system does not possess the accuracy necessary to measure fine eye movement. A company called "imec" developed a pair of ergonomic eye-tracking glasses equipped with a series of 5 EOG electrodes [61]. The glasses can reportedly process eye tracking data twice as fast as traditional eye-trackers (given the simplicity of EOG data vs IR images) and are highly portable with a battery life of 8-10 hours [62]. Altobelli et. al developed a custom low-cost EOG headset constructed using a 3D-printed plastic body and commercial EOG components [62]. The paper demonstrated the acquisition of a reliable EOG signal under a range of visual stimuli. To my knowledge, there are still no headsets which integrate virtual reality (VR) with precise EOG eye tracking. Our Bass Connections project, if fully implemented, would thus present a novel application in the context of existing MET systems.

Despite the advantages of EOG eye-tracking setups, there are a series of drawbacks which currently limit the use of EOG technology. Foremost, EOG systems are extremely sensitive to external noise [63]. Given the extremely low magnitude of the corneal retinal potential (often below 100 µV), it is likely for the incoming signal to be distorted before or during signal processing. External electro-magnetic interference, such as 60 Hz noise emanating from power lines, may induce significant error on both circuit components and the quality of the input signal. From our experiments, we found that the magnitude of 60 Hz noise alone may exceed any measurable resting potential across the eye. EOG electrodes are also sensitive to error if they are not firmly attached to the human subject. Other structures within the human face may produce measurable electric potentials which interfere with the

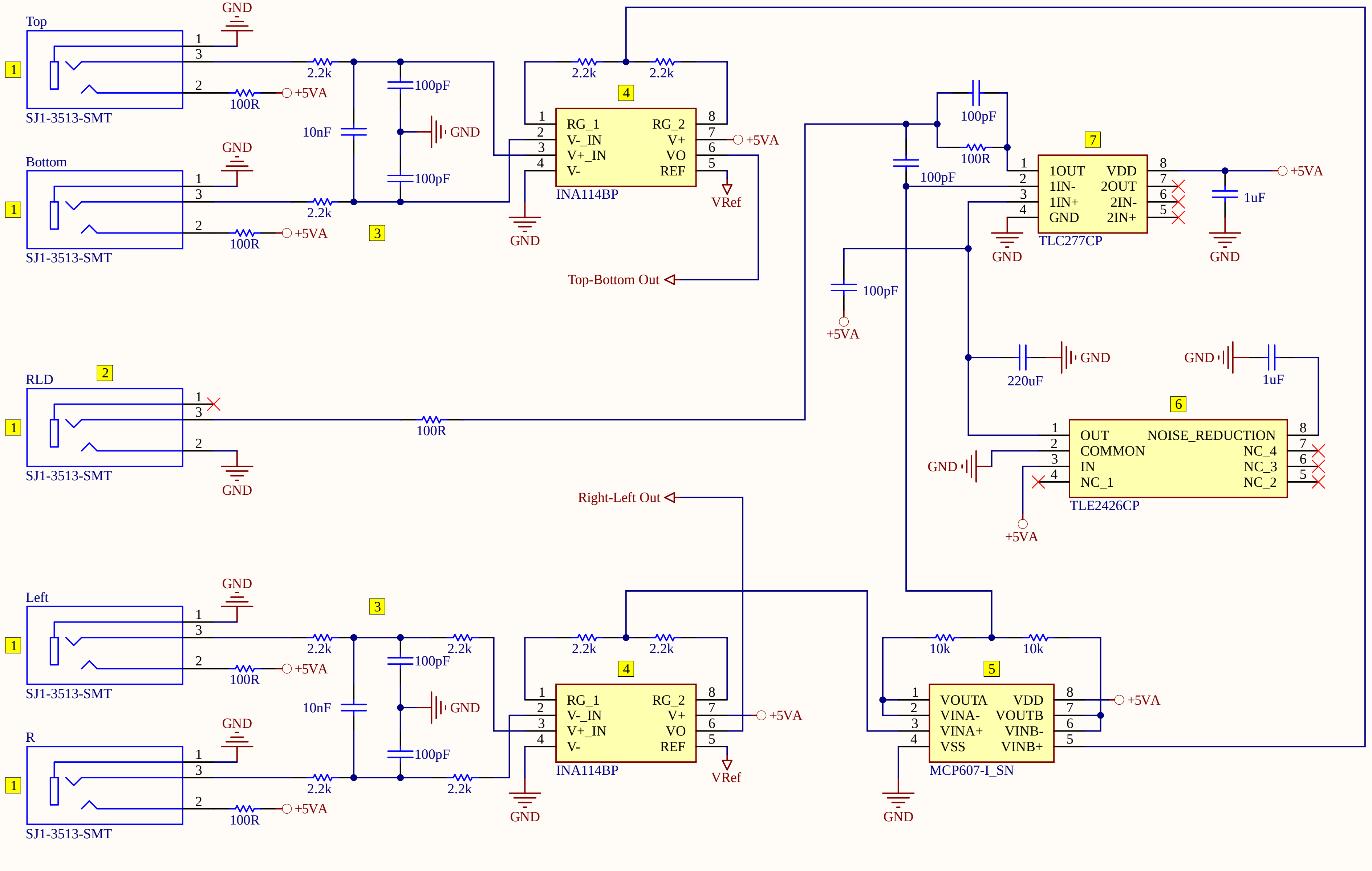
EOG data, such as from muscle contractions. Variable conditions on the subject's skin, such as relative moisture content, have bene known to alter skin impedance, and may result in error in the system output [63].

EOG systems also tend to display a high degree of baseline wander (BW) drift [42, 64, 65]. Baseline wander drift is very low frequency noise that results in a gradual rise or fall of the overall EOG signal. Baseline wander may result from a number of sources in EOG systems, such as a shift in the position of the electrodes, movement of the subject, or external electromagnetic interference [65]. It is often difficult to address baseline wander at the source, since it can be difficult to determine the exact cause of the drift. However, multiple processing techniques have been proposed to address the influence of baseline drift on signal quality [65, 66]. In 2018, Abrams et. al proposed a baseline drift mitigation process which uses a series of linear regressions to approximate the baseline value of the signal [previous Bass project]. This linear regression-based technique was found to work well on eye tracking data, reaching an error of less than 1.5 degrees when compared to the Eyelink Infrared system.

Physical Circuit



Labels: 1. AUX ports for EOG electrodes 2. AUX port for RLD electrode 3. High pass filters 4. INA114 Instrumentation Amplifiers 5. MCP607 Operational Amplifier 6. TLE2426 Voltage Reference 7. TLC Precision Operational Amplifier 8. Type H barrel cable port for power supply



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Circuit Annotations

1. Four Olimex Active EEG Electrodes[1] are fixed to the EOG goggles to capture the vertical and horizontal gaze components. The electrodes located above and below the left eye capture the vertical gaze component. The electrodes positioned to the right of the right eye and to the left of the left eye capture horizontal gaze component. The electrodes include an internal amplifier to strengthen the quality of the transmitted EOG signals. The electrodes terminate in a 3.5mm aux jack with three leads: two correspond to power/ground, and one carries the voltage information.
2. The electrodes are connected to the tin can circuit via four audio jack ports.[2] This model of audio jack consists of three leads, one which is used to carry the electrode data (#2), and two which are used for power. The lead carrying the electrode data is then connected to a low pass filter to begin signal processing. Unlike the other four electrodes, the electrode labeled "RLD" does not carry EOG data. In this case, "RLD" stands for "Right Leg Driving" or "Driven-Right-Leg" circuit, and is used to actively cancel the common mode voltage of the test subject [67]. An "ideal" operation amplifier returns a scaled difference of two input voltages at a constant gain. Actual operational amplifiers may behave slightly differently depending on a variety of factors, such as temperature or external electro-magnetic interference. One source of error results from the common mode voltage between the two inputs, which may be calculated as one-half times the difference of the two input voltages ($(V_1 - V_2) / 2$). Depending on the design, operational amplifiers add a small fraction of the common mode voltage to the output voltage. When the difference between the input voltages is large, the common mode error is generally insignificant compared to the magnitude of the desired output. However, the electric potential across a human eye is extremely small, meaning if a common voltage exists, it could potentially interfere with the proper function of the operational amplifier. The human body displays a small degree of electric capacitance, meaning humans can act as antennae for external electro-magnetic noise. During our experiments, we found this to hold especially true for 60 Hz noise generated by power lines. The RLD circuit works by taking the average voltage across all four sensing electrodes, inverting this voltage, and feeding it back to the human body. To ensure safety, the

[1] https://www.olimex.com/Products/EEG/Electrodes/EEG-AE/open-source-hardware
[2] https://www.cuidevices.com/product/resource/sj1-351x-smt.pdf

RLD electrode is isolated from the body using a set of unity-gain buffers before the final inverting op-amp.

3. The inputs from the right/left and top/bottom electrodes are routed to two low-pass filters with a cutoff frequency of 1592 Hz. This portion of the circuit eliminates high-frequency noise from the incoming signals that likely does not originate from the movement of the human eye.
4. The tin can circuit contains two INA114BP instrumentation amplifiers, one for both the right/left and top/bottom, electrode pairs.[3] This circuit uses the INA114BP over a standard operational amplifier as the INA114BP may precisely amplify small signals, such as those generated by the human eye. The INA114BP consists of three internal op-amps arranged to maximize the common-mode rejection ratio, being the ratio of the gain applied to the difference of the true signals, and the gain applied to the common mode voltage. The output of the INA114BP is wired directly to the LR OUT/TB OUT ports on the tin can circuit to be digitally processed by an oscilloscope.
5. The MCP607 is a pair of two operational amplifiers packaged in the same chip.[4] The MCP607 serves as a buffer between the human body and the circuit to prevent high currents from reaching the test subject through the RLD electrode.
6. The TLE2426 generates a constant reference voltage equivalent to one half of the supply voltage. The INA114BP instrumentation amplifiers center their output about this reference voltage. Without a reference voltage present, the instrumentation amplifiers would simply output 0 volts for all negative V_{in} since the INA114BP is a single-source amplifier. With a reference voltage, the INA114BP will map negative V_{in} to output voltages in the range 0 to $V_{ref}/2$ to avoid output clipping. [5]
7. The TLC277CP acts as a precision amplifier to connect the RLD circuit to the body.[6] In this case, the TLC227CP acts as an inverting amplifier so that its output effectively cancels the common mode voltage of the body.
8. As labelled on the physical circuit, the circuit is powered by a 5V battery pack terminating in an H-barrel power plug.

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[3] https://www.ti.com/lit/ds/symlink/ina114.pdf?HQS=dis-mous-null-mousermode-dsf-pf-null-wwe&ts=1639376200544&ref_url=https%253A%252F%252Fwww.mouser.com%252F

[4] https://www.mouser.com/datasheet/2/268/MCHPS02963_1-2520680.pdf

[5] https://www.ti.com/product/TLE2426

[6] https://www.ti.com/lit/ds/symlink/tlc277.pdf?HQS=dis-mous-null-mousermode-dsf-pf-null-wwe&ts=1639390223706&ref_url=https%253A%252F%252Fwww.mouser.com%252F

Conclusion and Future Work

This semester, I furthered my work towards building a mobile EOG eye-tracking system by assembling a preliminary physical EOG circuit. Across the semester, I gained valuable experience building a circuit over the stages of the initial design/planning process, ordering parts, and incremental testing. I also advanced my knowledge of the field of eye-tracking technologies, especially as related to concussion-diagnosis.

There are multiple areas for potential future work on this project. Foremost, I hope to validate the physical circuit I designed and achieve a working prototype. Given the experiences of past Bass Connections teams involved with the EOG-headset project, further work may potentially involve isolating the circuit from electro-magnetic interference and determining ways to ensure reliable contact between the test subject and the EOG electrodes. Ultimately, I hope to transfer the breadboarded circuit onto a PCB which may then be integrated into a VR headset or used for general research purposes.

References

[1] "EyeLink 1000 Plus." SR Research. https://www.sr-research.com/eyelink-1000-plus/ (accessed 4/23, 2022).

[2] J. A. Langlois, W. Rutland-Brown, and M. M. Wald, "The Epidemiology and Impact of Traumatic Brain Injury: A Brief Overview," *The Journal of Head Trauma Rehabilitation,* vol. 21, no. 5, pp. 375-378, 2006. [Online]. Available: https://journals.lww.com/headtraumarehab/Fulltext/2006/09000/The_Epidemiology_and_Impact_of_Traumatic_Brain.1.aspx.

[3] L. M. Ryan and D. L. Warden, "Post concussion syndrome," *International Review of Psychiatry,* vol. 15, no. 4, pp. 310-316, 2003-11-01 2003, doi: 10.1080/09540260310001606692.

[4] D. F. Meaney and D. H. Smith, "Biomechanics of Concussion," *Clinics in Sports Medicine,* vol. 30, no. 1, pp. 19-31, 2011-01-01 2011, doi: 10.1016/j.csm.2010.08.009.

[5] K. L. O'Connor, S. Rowson, S. M. Duma, and S. P. Broglio, "Head-Impact–Measurement Devices: A Systematic Review," *Journal of Athletic Training,* vol. 52, no. 3, pp. 206-227, 2017-03-01 2017, doi: 10.4085/1062-6050.52.2.05.

[6] M. McCrea, T. Hammeke, G. Olsen, P. Leo, and K. Guskiewicz, "Unreported concussion in high school football players: implications for prevention," (in eng), *Clin J Sport Med,* vol. 14, no. 1, pp. 13-7, Jan 2004, doi: 10.1097/00042752-200401000-00003.

[7] C. H. Tator, "Concussions and their consequences: current diagnosis, management and prevention," *Canadian Medical Association Journal,* vol. 185, no. 11, pp. 975-979, 2013, doi: 10.1503/cmaj.120039.

[8] D. I. Graham, J. H. Adams, J. A. R. Nicoll, W. L. Maxwell, and T. A. Gennarelli, "The Nature, Distribution and Causes of Traumatic Brain Injury," *Brain Pathology,* vol. 5, no. 4, pp. 397-406, 1995-10-01 1995, doi: 10.1111/j.1750-3639.1995.tb00618.x.

[9] L. M. Thomas, V. L. Roberts, and E. S. Gurdjian, "Experimental intracranial pressure gradients in the human skull.," *Journal of Neurology, Neurosurgery & Psychiatry,* vol. 29, no. 5, pp. 404-411, 1966-10-01 1966, doi: 10.1136/jnnp.29.5.404.

[10] E. S. H. W. G. P. L. M. E. F. G. L. H. R. Gurdjian, *Intracranial pressure and acceleration accompanying head impacts in human cadavers*. (in English), 1961.

[11] S. Rowson *et al.*, "Rotational Head Kinematics in Football Impacts: An Injury Risk Function for Concussion," *Annals of Biomedical Engineering,* vol. 40, no. 1, pp. 1-13, 2012-01-01 2012, doi: 10.1007/s10439-011-0392-4.

[12] F. Unterharnscheidt and L. S. Higgins, "Traumatic lesions of brain and spinal cord due to nondeforming angular acceleration of the head," (in eng), *Tex Rep Biol Med,* vol. 27, no. 1, pp. 127-66, Spring 1969.

[13] B. R. Donnelly and J. Medige, "Shear Properties of Human Brain Tissue," *Journal of Biomechanical Engineering,* vol. 119, no. 4, pp. 423-432, 1997, doi: 10.1115/1.2798289.

[14] A. K. Ommaya and T. A. Gennarelli, "CEREBRAL CONCUSSION AND TRAUMATIC UNCONSCIOUSNESS," *Brain,* vol. 97, no. 1, pp. 633-654, 1974-01-01 1974, doi: 10.1093/brain/97.1.633.

[15] C. C. Giza and D. A. Hovda, "The Neurometabolic Cascade of Concussion," (in eng), *Journal of athletic training,* vol. 36, no. 3, pp. 228-235, 2001. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/12937489

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC155411/.

[16] Y. Katayama, D. P. Becker, T. Tamura, and D. A. Hovda, "Massive increases in extracellular potassium and the indiscriminate release of glutamate following concussive brain injury," *Journal of Neurosurgery,* vol. 73, no. 6, pp. 889-900, 1990-12-01 1990, doi: 10.3171/jns.1990.73.6.0889.

[17] C. C. Giza and D. A. Hovda, "The New Neurometabolic Cascade of Concussion," *Neurosurgery,* vol. 75, pp. S24-S33, 2014-10-01 2014, doi: 10.1227/neu.0000000000000505.

[18] A. Yoshino, D. A. Hovda, T. Kawamata, Y. Katayama, and D. P. Becker, "Dynamic changes in local cerebral glucose utilization following cerebral concussion in rats: evidence of a hyper- and subsequent hypometabolic state," *Brain Research,* vol. 561, no. 1, pp. 106-119, 1991-10-01 1991, doi: 10.1016/0006-8993(91)90755-k.

[19] M. R. Lovell *et al.*, "Measurement of Symptoms Following Sports-Related Concussion: Reliability and Normative Data for the Post-Concussion Scale," *Applied Neuropsychology,* vol. 13, no. 3, pp. 166-174, 2006-09-01 2006, doi: 10.1207/s15324826an1303_4.

[20] M. McCrea *et al.*, "Incidence, Clinical Course, and Predictors of Prolonged Recovery Time Following Sport-Related Concussion in High School and College Athletes," *Journal of the International Neuropsychological Society,* vol. 19, no. 1, pp. 22-33, 2013, doi: 10.1017/s1355617712000872.

[21] S. Amadio *et al.*, "Chronic Traumatic Encephalopathy in Professional American Football Players: Where Are We Now?," *Frontiers in Neurology | www.frontiersin.org,* vol. 1, pp. 445-445, 2018, doi: 10.3389/fneur.2018.00445.

[22] J. Mez *et al.*, "Clinicopathological evaluation of chronic traumatic encephalopathy in players of American football," *JAMA - Journal of the American Medical Association,* vol. 318, no. 4, pp. 360-370, 2017/7// 2017, doi: 10.1001/JAMA.2017.8334.

[23] J. Ward, J. Williams, and S. Manchester, "111 N.F.L. Brains. All But One Had C.T.E. - The New York Times," in *The New York Times*, ed, 2017.

[24] K. D. Barber Foss *et al.*, "Relative Head Impact Exposure and Brain White Matter Alterations After a Single Season of Competitive Football: A Pilot Comparison of Youth Versus High School Football," *Clinical Journal of Sport Medicine,* vol. 29, no. 6, 2019. [Online]. Available: https://journals.lww.com/cjsportsmed/Fulltext/2019/11000/Relative_Head_Impact_Exposure_and_Brain_White.2.aspx.

[25] M. L. Lipton *et al.*, "Soccer Heading Is Associated with White Matter Microstructural and Cognitive Abnormalities," *Radiology,* vol. 268, no. 3, pp. 850-857, 2013-09-01 2013, doi: 10.1148/radiol.13130545.

[26] E. A. Harrison, "The First Concussion Crisis: Head Injury and Evidence in Early American Football," *American Journal of Public Health,* vol. 104, no. 5, pp. 822-833, 2014, doi: 10.2105/AJPH.2013.301840.

[27] S. P. Broglio, K. M. Guskiewicz, and J. Norwig, "If You're Not Measuring, You're Guessing: The Advent of Objective Concussion Assessments," *Journal of Athletic Training,* vol. 52, no. 3, pp. 160-166, 2017-03-01 2017, doi: 10.4085/1062-6050-51.9.05.

[28] J. S. Kutcher and C. C. Giza, "Sports Concussion Diagnosis and Management," *CONTINUUM: Lifelong Learning in Neurology,* vol. 20, pp. 1552-1569, 2014-12-01 2014, doi: 10.1212/01.con.0000458974.78766.58.

[29] "Premier Lacrosse League Adopts Eye-Sync as Part of Concussion Manageme," ed.

[30] "Official Rules 2021 Season w ww.theaudl.com," ed.

[31] "Concussion Safety Protocol Management," in *NCAA*, ed, 2021.

[32] C. C. Giza and D. A. Hovda, "The Neurometabolic Cascade of Concussion," in "Journal of Athletic Training," Association, Inc, 2001, vol. 36. [Online]. Available: www.journalofathletictraining.org

[33] M. Mccrea *et al.*, "Standard regression-based methods for measuring recovery after

sport-related concussion," *Journal of the International Neuropsychological Society,* vol. 11, no. 1, pp. 58-69, 2005-01-01 2005, doi: 10.1017/s1355617705050083.
[34] A. Fedor and J. Gunstad, "Limited Knowledge of Concussion Symptoms in College Athletes," *Applied Neuropsychology: Adult,* vol. 22, no. 2, pp. 108-113, 2015-03-04 2015, doi: 10.1080/23279095.2013.860604.
[35] R. Vagnozzi *et al.*, "Assessment of metabolic brain damage and recovery following mild traumatic brain injury: a multicentre, proton magnetic resonance spectroscopic study in concussed patients," *Brain,* vol. 133, no. 11, pp. 3232-3242, 2010-11-01 2010, doi: 10.1093/brain/awq200.
[36] M. Mccrea *et al.*, "Association of Blood Biomarkers With Acute Sport-Related Concussion in Collegiate Athletes," *JAMA Network Open,* vol. 3, no. 1, p. e1919771, 2020-01-24 2020, doi: 10.1001/jamanetworkopen.2019.19771.
[37] N. Snegireva, W. Derman, J. Patricios, and K. E. Welman, "Eye tracking technology in sports-related concussion: a systematic review and meta-analysis," *Physiological Measurement,* vol. 39, pp. 12TR01 , pmid = 30523971 , publisher = IOP Publishing, 12 2018, doi: 10.1088/1361-6579/AAEF44.
[38] J. P. Mihalik *et al.*, "Do Head Injury Biomechanics Predict Concussion Clinical Recovery in College American Football Players?," *Annals of Biomedical Engineering,* vol. 48, no. 11, pp. 2555-2565, 2020-11-01 2020, doi: 10.1007/s10439-020-02658-y.
[39] S. Rowson and S. M. Duma, "Brain Injury Prediction: Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration," *Annals of Biomedical Engineering,* vol. 41, no. 5, pp. 873-882, 2013-05-01 2013, doi: 10.1007/s10439-012-0731-0.
[40] R. Jadischke, D. C. Viano, N. Dau, A. I. King, and J. McCarthy, "On the accuracy of the Head Impact Telemetry (HIT) System used in football helmets," *Journal of Biomechanics,* vol. 46, no. 13, pp. 2310-2315, 2013/09/03/ 2013, doi: https://doi.org/10.1016/j.jbiomech.2013.05.030.
[41] K. J. Ciuffreda, N. Kapoor, D. Rutner, I. B. Suchoff, M. E. Han, and S. Craig, "Occurrence of oculomotor dysfunctions in acquired brain injury: A retrospective analysis," *Optometry - Journal of the American Optometric Association,* vol. 78, no. 4, pp. 155-161, 2007, doi: 10.1016/j.optm.2006.11.011.
[42] A. M. Boukadoum and P. Y. Ktonas, "EOG-Based Recording and Automated Detection of Sleep Rapid Eye Movements: A Critical Review, and Some Recommendations," *Psychophysiology,* vol. 23, pp. 598-611 , publisher = John Wiley & Sons, Ltd, 9 1986, doi: 10.1111/J.1469-8986.1986.TB00678.X.
[43] B. Andreas, A. W. Jamie, G. Hans, and T. Gerhard, "Eye movement analysis for activity recognition using electrooculography," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 33, pp. 741-753, 2011, doi: 10.1109/TPAMI.2010.86 , issue = 4.
[44] B. Andreas, R. Daniel, and T. Gerhard, "Wearable EOG goggles: Seamless sensing and context-awareness in everyday environments," *Journal of Ambient Intelligence and Smart Environments,* vol. 1, pp. 157-171, 2009, doi: 10.3233/AIS-2009-0020.
[45] H. Wolfgang, E. Koenig, T. Peter, K. Daniela, and S. Z. David, "Electrooculography: technical standards and applications," 2010.
[46] J. Drewes, W. Zhu, Y. Hu, and X. Hu, "Smaller Is Better: Drift in Gaze Measurements due to Pupil Dynamics," *PLoS ONE,* vol. 9, no. 10, p. e111197, 2014-10-22 2014, doi: 10.1371/journal.pone.0111197.
[47] H. Deubel and W. X. Schneider, "Saccade target selection and object recognition: Evidence for a common attentional mechanism," *Vision Research,* vol. 36, no. 12, pp. 1827-1837, 1996-06-01 1996, doi: 10.1016/0042-6989(95)00294-4.

[48] L. Alberto, F. Francisco, Y. David, Á. Constantina, and P. Octavian, "Development of a computer writing system based on EOG," *Sensors (Switzerland),* vol. 17, 7 , pmid = 28672863 , publisher = MDPI AG 2017, doi: 10.3390/s17071505.
[49] A. Shideh Kabiri *et al.*, "Imperceptible electrooculography graphene sensor system for human–robot interface," *npj 2D Materials and Applications 2018 2:1,* vol. 2, pp. 1-7 , publisher = Nature Publishing Group, 7 2018, doi: 10.1038/s41699-018-0064-4.
[50] B. Estrany, P. Fuster, A. Garcia, and Y. Luo, "Human computer interface by EOG tracking," presented at the 1st International Conference on Pervasive Technologies Related to Assistive Environments, PETRA 2008, 2008.
[51] K. Eghbal-Azar and T. Widlok, "Potentials and Limitations of Mobile Eye Tracking in Visitor Studies," *Social Science Computer Review,* vol. 31, no. 1, pp. 103-118, 2013-02-01 2013, doi: 10.1177/0894439312453565.
[52] M. Meißner, J. Pfeiffer, T. Pfeiffer, and H. Oppewal, "Combining virtual reality and mobile eye tracking to provide a naturalistic experimental environment for shopper research," *Journal of Business Research,* vol. 100, pp. 445-458, 2019-07-01 2019, doi: 10.1016/j.jbusres.2017.09.028.
[53] T. Harwood and M. Jones, "Mobile Eye-Tracking in Retail Research," in *Current Trends in Eye Tracking Research*: Springer International Publishing, 2014, pp. 183-199.
[54] K. Krafka *et al.*, "Eye Tracking for Everyone," 2016.
[55] M. Kassner, W. Patera, and A. Bulling, "Pupil," in *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*, 2014-09-13 2014: ACM, doi: 10.1145/2638728.2641695.
[56] S. Chugh, "An Eye Tracking System for a Virtual Reality Headset," M.A.S., University of Toronto (Canada), Ann Arbor, 28094598, 2020. [Online]. Available: https://login.proxy.lib.duke.edu/login?url=https://www.proquest.com/dissertations-theses/eye-tracking-system-virtual-reality-headset/docview/2467610518/se-2?accountid=10598

https://libkey.io/libraries/229/openurl?genre=dissertations&au=Chugh%2C+Soumil&aulast=Chugh&issn=&isbn=9798698549024&title=An+Eye+Tracking+System+for+a+Virtual+Reality+Headset&jtitle=&pubname=An+Eye+Tracking+System+for+a+Virtual+Reality+Headset&btitle=&atitle=&volume=&issue=&spage=&date=2020&doi=&sid=ProQuest

https://PM6MT7VG3J.search.serialssolutions.com?ctx_ver=Z39.88-2004&ctx_enc=info:ofi/enc:UTF-8&rfr_id=info:sid/ProQuest+Dissertations+%26+Theses+Global&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&rft.genre=dissertations&rft.jtitle=&rft.atitle=&rft.au=Chugh%2C+Soumil&rft.aulast=Chugh&rft.aufirst=Soumil&rft.date=2020-01-01&rft.volume=&rft.issue=&rft.spage=&rft.isbn=9798698549024&rft.btitle=&rft.title=An+Eye+Tracking+System+for+a+Virtual+Reality+Headset&rft.issn=&rft_id=info:doi/
[57] "Tobii Pro Glasses 3." Tobii AB. https://www.tobiipro.com/product-listing/tobii-pro-glasses-3/ (accessed April 30, 2022).
[58] "FOVE: The World's First Eye Tracking Virtual Reality Headset." Kickstarter. https://www.kickstarter.com/projects/fove/fove-the-worlds-first-eye-tracking-virtual-reality (accessed April 30, 2022).
[59] J. Shimizu and G. Chernyshov, "Eye Movement Interactions in Google Cardboard using a Low Cost EOG Setup," 2016. [Online]. Available: https://dl.acm.org/doi/pdf/10.1145/2968219.2968274.
[60] "Frame." J!NS MEME. https://jinsmeme.com/frame/ (accessed 2022).

[61] "WEARABLE EYE-TRACKING." imec. https://www.futuresummits.com/admin/storage/itf2019/gvdlow-cost-eyemovement.pdf (accessed 2022).
[62] F. Altobelli, "ElectroOculoGraphy (EOG) Eye-Tracking for Virtual Reality," Master in Integrated Product Design Master Thesis, Faculty of Industrial Design Engineering, TU Delft, 2019. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid:59c0e444-72c8-42e3-b29d-b0db150b1450?collection=education
[63] J. Ryu, M. Lee, and D.-H. Kim, "EOG-based eye tracking protocol using baseline drift removal algorithm for long-term eye movement detection," *Expert Systems with Applications,* vol. 131, pp. 275-287, 2019, doi: 10.1016/j.eswa.2019.04.039.
[64] D. Qiuping, T. Kaiyu, and L. Guang, "Development of an EOG (electro-oculography) based human-computer interface," *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings,* vol. 7 VOLS, pp. 6829-6831, 2005, doi: 10.1109/IEMBS.2005.1616073.
[65] B. Changhoon, G. Yongsook, and S. Jong-Mo, "IFMBE Proceedings 45 - Real-Time Baseline Wander Removal from Electrooculography Using Probabilistic Baseline Prediction ,," doi: 10.1007/978-3-319-11128-5_20.
[66] T. Mohammad Ali and M. Behzad, "A Wavelet Packets Approach to Electrocardiograph Baseline Drift Cancellation," *International Journal of Biomedical Imaging,* pp. 1-9 , publisher = Hindawi Publishing Corporation, 2006, doi: 10.1155/IJBI/2006/97157.
[67] W. Bruce and W. John, "Driven-Right-Leg Circuit Design," *IEEE Transactions of Biomedical Engineering,* vol. BME-30, pp. 62-66, 1 1983. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4121504.