WEARABLE BIOSENSORS: A NEW PORTAL TO THE BRAIN

By Michael Schuette, Andrew Junker, and Thomas P. Reynolds

Over the past few years, computers have evolved to become truly portable devices. Every current smartphone has more intelligence than most personal computers had only a decade ago. This has enabled novel applications and opportunities in every aspect of our lives, including entertainment, learning, data analysis, and rehabilitation, and has spawned new levels of connection between man and machine. This evolution has not been limited to just the processing level, but also includes input devices like touchscreens, word recognition, and even motion sensors that are now important pieces in the evolution of these applications. However, one last frontier remains: we are still not capable of directly communicating our thoughts to a computer.

The brain is our best protected organ, and, despite centuries of research unraveling its microcircuitry and local physiology, it still remains the least understood. We still lack even the most basic understanding of how sensory inputs are combined with pre-existing data in the form of memory and associations to trigger simple reactions, let alone more complex behavioral or cognitive responses. Interestingly though, global reactions of large brain areas may be more reliable indicators of high-level brain states. Those high-level states include recognition of prior knowledge and decision-making, as well as pathologic states related to chronic or acute depression, or addiction relapses.

Detecting brain states is difficult and requires sophisticated electroencephalograph (EEG) or functional MRI (fMRI) systems. EEG and fMRI systems are complex, bulky, and expensive, making them impractical for mass deployment or for large scale data capture, especially in a real life environment. However, it may not be necessary to rely on isolated brain activity alone, since many of the brain's responses are projected to muscles outside the skull, courtesy of cranial nerves, and manifest themselves as facial responses. Examples are pupil and eye-lid reflexes, blushing, twitching, and other involuntary responses, all of which result in electrical activity that can be easily picked up using low-cost consumer-grade sensors and electronics. This cost reduction and miniaturization enables the mass deployment of wearable biosensor systems supporting the development of all kinds of new applications. We can now begin to acquire large data sets from a significant number of individuals and subject them to big data analytics, including correlation with actual behavior of the individuals over time.

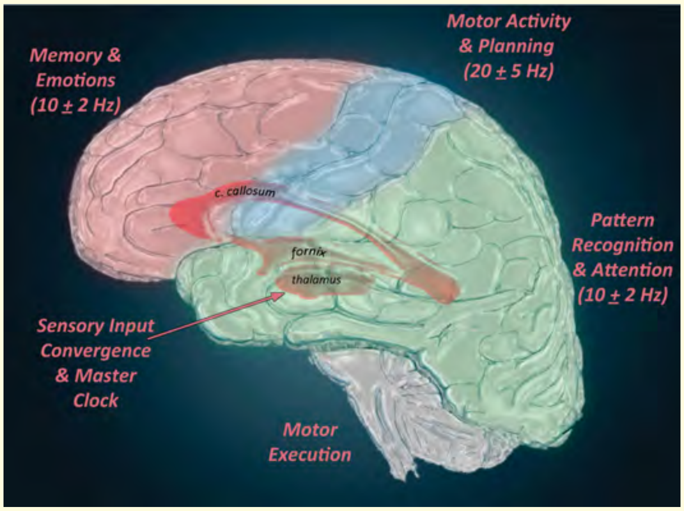

Figure 1 | Overview of the different brainwave clock domains of the human brain

The Origin of Electrical Brain Activity

Every physiological activity of a living cell creates a change in its electrical potential across the cell's membrane; that is, the voltage between the intracellular space and the outside world. The change in electrical potential in individual cells also plays an important role in the communication between individual neurons through so-called electrical synapses or gap junctions, which allow propagation of brain activity across a large area. This electrical signaling complements chemical synaptic signaling, causing a dwelling chain-reaction across all connected cells and resulting in amplification of the electrical signal by several orders of magnitude. Independent of specific events, these electrical discharges also occur as periodic oscillations, which are important for the synchronization between different sensory modalities such as vision, touch, and hearing. Without this synchronization, the different inputs would remain unrelated and could not be combined by the brain to identify objects or trigger even higher associative processes.[1,2]

Within the field of neuroscience, these periodic electrical activities are known as brain waves. Brain waves are divided into several groups based on their frequency range. The most prominent brain waves are in the spectrum of 8-12 Hz (known as alpha waves) and originate from pacemaker cells in the thalamus, from where they propagate to the sensory cortex areas (visual, auditory, and tactile) and the frontal cortical areas (memory, associations, and emotions).[3]

Intriguingly, the "motor" cortex hums at approximately twice the frequency of the sensory areas (15-30 Hz, or so-called beta waves), which is an elegant way to allow fast feed forward from the alpha spectrum while suppressing feedback contamination from the motor cortex to the sensory and emotional areas. For EEG-based control and monitoring, this allows frequency-based separation of merely "reactive" vs. "active" brain tasks.

As a result of the mass action mentioned, brain waves can be recorded outside the skull with reasonable accuracy. This usually requires clinical-grade electroencephalogram (EEG) devices that are expensive and rely heavily on a "clean" environment that is not polluted by external electromagnetic interference (EMI).

The Brain-Body Connection

It is a "no brainer" that the brain governs the body on a cognitive level. In addition, reflexes originating in the brain serve self-preservation (parasympathetic), performance enhancement (sympathetic), or communication (facial innervation) purposes which directly mirror emotional and cognitive states. These reflexes involve a fast neural response of the cranial nerves innervating the face. While those reflexes are subconscious or unconscious responses to outside events and bypass most higher cognitive processes, the electrical activity of muscles that twitch in response to these signals is easily captured in the form of an electromyogram (EMG). Twitches of eye muscles can also be recorded indirectly through electrooculogram (EOG). This is important because it opens up an indirect way to get insight into subconscious brain states or responses by using efferent projections to the face and capturing the amplified EMG potentials of facial reactions.

Building a Low-Cost, Wearable Biopotential Monitor

Five years ago, BCInet started the development of a low-cost, consumer-grade EEG, EMG, and EOG (collectively, biopotentials) device named the Neural Impulse Actuator™ (NIA). The NIA was introduced into the market as a Brain-Computer Interface (BCI) device targeted for use as a personal computer input or control device for a wide customer base ranging from computer gamers to the disability field, including locked-in syndrome.

The NIA was designed as a very low-cost, simple-to-use, and wearable brain activity monitor with a software interface for application development. The NIA captures electrical signals at the forehead using medical sensors contained within a small, portable, and unobtrusive headband (as opposed to traditional EEG skullcaps with multiple sensors and wires connected to an apparatus sitting on a wheeled cart). The signals are then processed through a controller-amplifier for filtering, digitizing, and serialization before sending a single composite data stream to a host platform.

BCInet's patented signal processing software runs presently on the host platform, whether it's a PC, smartphone, tablet, or other processing device. The software de-convolutes the data stream into EEG, EMG, and EOG. EEG signals are further separated into individual alpha, beta, gamma, and theta bands. These signals are then available for monitoring or control.

Monitoring: The representation of the various signals can be displayed in several ways to fit the needs of a target application. One possibility is to incorporate feedback directly into applications. This enables individuals to log brain states for later correlation with environmental events, or else instantly see results and get alerted to positive or negative changes in brain activity. This combination of monitoring and feedback opens opportunities for EEG-, EMG-, and EOG-based biofeedback to enhance quality of life including improved health and productivity.

Control: Mapping of the EEG, EMG, and EOG signals, through software, can be bound to any keyboard key, mouse click, or external controller device for various applications.

The addition of a software development kit (SDK) provides programmable access to BCInet's hardware reference designs in order to encourage new application development.

Applications

We originally developed the NIA with the goal of creating a low-cost, cutting edge computer input device to increase the fun of playing computer games and enhance immersion in gaming applications. The underlying strategy was to decrease the layers of abstraction such as learning key strokes and mouse click combinations. Instead, the NIA converts

Figure 2 | The Neural Impulse Actuator: A low-cost combination EEG, EMG, and EOG device

biopotentials detected with the headband sensors into control functions. Because the device is simple to wear and learn, the possible applications extend far beyond gaming, to potential diagnostic and therapeutic uses.

Wearable sensors carry the promise of collecting significant information that can be applied in researching causes and new cures for multiple types of disorders. The low-cost, wearable approach brings new solutions to significant numbers of individuals to improve their lives. Applications, based on correlation of EMG and EOG with "classical" EEG responses appear almost endless and could include detection of events not only important to the Intelligence Community but also for health management, addiction relapses, rehabilitation, state-dependent memory training, and other opportunities to improve the interface between man and machine. Briefly, examples of these application areas include:

- Prior knowledge testing
- Subconscious unusual event identification
- Identification of pre-relapse states
- Mindfulness preparation and training
- Attention/tension-based device control
- Rehabilitation
- Fun and exercise through games

One intriguing class of applications involves the response of the brain when exposed to visual stimuli the observer recognizes. When a person recognizes a stimulus, a so-called event-related potential (ERP) can be detected via EEG. Because the ERP is well-known to occur 300 milliseconds after the stimulus, this EEG signature is called the P300 response. Interestingly, ERPs may lag behind physical reaction times, which typically occur after only 150-200 milliseconds.[4] During the testing of the NIA, we witnessed an unexpected phenomenon in the form of reduced reaction times in first-person shooter games. Players could shoot at enemy bots even before they could actually see them at a conscious level.[5] The phenomenon was robust and reaction times were even shorter than using a manual, click-based trigger. It is reasonable to conclude that the same type of reflex-based reaction could be used to identify other subconscious recognition events.

Specific Examples of Applications

For those with communications disabilities, wearable biosensors enable control of many different types of devices for immediate improvement in quality of life. They allow users to operate computer applications, keyboards, and cursors, enabling communication with the outside world in a way that was not previously possible.

Quadriplegia and Paralysis: Thousands of people are afflicted with various forms and levels of paralysis. Considering the level of variation in the extent of affliction, no single approach is best for all levels of disability. Wearable biosensors provide the best flexibility for a custom configuration based on the specific needs of the user.

Traumatic Brain Injury (TBI): For returning veterans with physical injuries such as TBI, loss of limbs, and spinal cord injuries, wearable biosensors allow for control of many different types of devices that can bring an immediate improvement to their lives. Examples of these devices include the use of computers, wheelchairs, prosthetic limbs, and more.

Regardless of the specific type of application, users will find that EMG is the easiest to control, followed by EOG, and then EEG. Most users will rely on a combination of all three in aggregate for control and monitoring. Rather than discarding EMG or EOG as irrelevant for monitoring brain activity, the entire spectrum is considered a unified and valuable resource with different aspects complementing and confirming each other. Moreover, successful adaptation of a novel device heavily depends on the fastest possible learning curve. Additional incentives are affordability, ease of wear, and, most importantly, the simple fact that it works.

Portable computers such as smartphones and tablets have created novel platforms for a grand scale deployment of wearable biosensors. Monitoring brain, attention, and reflex activity through EEG, EOG, and EMG events and correlating them with environmental stimuli opens a wealth of opportunities for understanding social behavior. Insights gained from those data can be used to develop targeted applications for real-time feedback that can be used for therapeutic and preventive interference with disorders. In addition, wearable biosensors can be used to develop control applications running on the portable platforms.

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REFERENCES

1 Oliver Sacks: The Mind's Eye (http://www.npr.org/books/titles/137993453/the-minds-eye)
2 Christof Koch: http://ttbook.org/book/transcript/transcript-christof-koch-uncut
3 Fuster, Joaquin (2008). *The prefrontal cortex* (4 ed.). Oxford, UK: Elsevier. p. 126. ISBN 978-0-12-373644-4
4 Human Benchmark (http://www.humanbenchmark.com/tests/reactiontime/stats.php)
5 http://www.youtube.com/watch?v=69skEJB6lq0