BRAINATHLON:
Enhancing Brainwave Control Through Brain-Controlled Game Play

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Abstract

The field of brain-computer interface research has been rapidly expanding in recent years and has a wide range of interesting and compelling uses. EEG-based brain-computer interfaces currently allow users to type, play games, create music, or control prosthetic limbs.

This thesis describes the development of Brainathlon, an open source software game that is controlled by the players' brainwave activity. An electroencephalogram (EEG) monitors the player's brainwaves. These waves are fed into the computer, analyzed, and used to control the game play. The game provides users with real-time feedback on current brain activity and rewards activity in configurable frequency ranges. This feedback leads to enhanced conscious control of brainwave activity.

The software that was developed includes a reusable library of EEG monitoring, filtering, and analysis tools that can be used to create future EEG-based applications. The software was built to work with ModularEEG, an open source brainwave monitoring device. The reusable Brainathlon libraries will provide software developers with a toolkit to facilitate the creation of low cost brain-computer interface applications for the ModularEEG device.

Acknowledgements

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This paper is dedicated to the memory of my father, who always encouraged me to figure things out for myself and insisted that I could solve any problem I set my mind to. I dived in well over my head with this work and it seems you were right; I managed to figure it all out in the end.

Contents

Chapter 1

Introduction

Controlling a computer with one's mind may sound like science fiction, but brain-computer interfaces currently exist, and innovative research is rapidly expanding the level of control that is achievable. Researchers, psychologists, artists, and others have been experimenting with non-invasive brain-computer interfaces that read brain signals with an electroencephalogram (EEG). EEG-based brain-computer interfaces use sensors placed on the head to detect brainwaves and feed them into a computer as input.

EEG-based interfaces are being used for a wide range of applications. Clinical psychologists employ brain interfaces to treat a number of conditions, including attention deficit hyperactivity disorder (ADHD), epilepsy, and alcoholism [10]. Researchers are creating brain-interfaces to aid disabled users who are unable to use typical computer interfaces [30]. Artists and musicians have also been experimenting with brain-interfaces to create unusual art, music, and performances [52][41].

Current research suggests that learning to consciously control our brainwave states could help us increase our ability to concentrate and decrease our stress levels [43]. Despite the apparent benefits, access to neurofeedback training is limited. EEG devices and training software are typically expensive and regulated by the medical industry. Affordable EEG hardware is slowly becoming available, but software remains limited. Although EEG research has increased, there remains a lack of free software available to enhance brainwave mastery.

This thesis describes the design and development of a new open source software game that can be configured to encourage brainwave activity in user-specified frequency ranges. The work includes both a software game to strengthen brainwave control and a software library that can be used to create other brain-controlled applications.

The game is called Brainathlon. Like a triathlon, it consists of separate mini-games, called courses, that reward brainwave activity in configurable frequency ranges. A single user can play the game alone, or two players can compete against each other. When played in two-player mode, the player who wins the most courses will win the game. This game can be used to gain better control of brainwave activity and to increase brainwave frequencies associated with certain mental states such as relaxation or mental focus. The Brainathlon project source code and documentation are available at `http://www.webkitchen.com/brainathlon`.

The open source software movement has created a collaborative model for software that can leverage the expertise of the global community [44]. Open source software isn't just about licensing. In an open source project, developers from different parts of the world and different disciplines can exchange knowledge and ideas. Since brain-computer interface development is an interdisciplinary field requiring knowledge of hardware, digital signal processing, artificial intelligence, neurology, and psychology, the open source philosophy provides an ideal foundation for developing brain-computer interface applications.

Chapter 1 contains a brief explanation of brainwaves and EEG, and provides some historical background on the history of brainwave studies. It also provides an overview of the main areas of research and experimentation with EEG-based applications. Chapter 2 examines the requirements for building a brain-controlled application, and provides a description of the Brainathlon game and its reusable software libraries. Chapter 3 describes the design and implementation details of the game and libraries. Chapter 4 discusses the experiment conducted to evaluate the game's effectiveness at enhancing control of brainwave activity. Chapter 5 concludes with a summary of the contributions of this work.

1.1 Brainwave Rhythms

The individual neurons in our brains communicate with one another by sending tiny electrochemical signals from one cell to another. The electrical signal of an individual neuron is far too small to be detected by an electrode placed on the scalp. However, when thousands of neurons are activated, each contributing its small electrical current, this generates a signal that is strong enough to be detected by an electroencephalogram (EEG) device [13][5].

If a group of neurons is activated synchronously, the sum of the activity will result in one large signal detectable at the scalp. In contrast, if the neurons in the group fire asynchronously, the sum of activity will result in a smaller, irregular signal. Therefore, a large amount of activity can still result in a low amplitude signal if the activity is slightly spread out in time. In contrast, a high amplitude signal is the result of rhythmic, synchronous activity [5].

Brainwaves are commonly categorized into 4 different frequency bands, or types, known as delta, theta, alpha, and beta waves. Each of these wave types often correlates with different mental states. Table 1.1 lists the different bands and their associated mental states.

Wave Type	**Frequency**	**Associated Mental States**
Delta	0-4 Hz	Deep sleep
Theta	4-8 Hz	Creativity, drifting thoughts, dream sleep
Alpha	8-12 Hz	Relaxation, calmness, abstract thinking
Beta-low	12-15 Hz	Relaxed focus
Beta-medium	15-20 Hz	High alertness, mental activity
Beta-high	20+ Hz	Agitation, anxiety

Table 1.1: Brainwave types and their associated mental states [61][43]

Delta activity is associated with deep sleep and is the dominant wave rhythm in infants. Theta activity is prevalent during dream sleep, meditation, and creative inspiration. Theta levels are commonly higher in children than in adults and are often very strong in children with attention deficit disorder. Alpha activity is associated with tranquility and relaxation. Simply closing one's eyes can generate increased alpha waves. Beta activity is associated with an alert state of mind, concentration, and mental activity [61].

Beta waves are sometimes further divided into low, medium, and high beta bands. Low beta is associated with moderate mental activity, medium beta is associated with high alertness and intense mental activity, and high beta is associated with hyper-awareness, stress, and anxiety.

The high-frequency waves (beta and alpha) dominate when awake. In this state, the brain is actively processing information, with many neurons firing, but not necessarily firing simultaneously with their neighbors. As a result, fast-wave activity tends to be more asynchronous, which creates a low amplitude signal. In contrast, low-frequency waves (delta and theta) dominate during sleep, when the brain is not busy processing sensory information. This slow-wave activity is more synchronous, which results in a higher amplitude signal [5].

1.2 The Electroencephalogram

Electrical activity inside the brain can be detected with electrodes placed on the scalp or forehead. Small differences in voltage are measured between pairs of electrodes, and the resulting signal is amplified and drawn in the form of a wave. This drawing is called an electroencephalogram, or EEG. Often the term EEG is also used as an abbreviation for electroencephalography, which is the entire process of recording brain activity. In this paper, we are using the term EEG to describe the entire process.

Digital computer technology is now commonly used to implement EEG brain-computer interfaces. Current methods often sample, digitize, and filter waves into their component frequencies. Digital signal processing techniques can be used to divide the signals into different frequency bands, forming a spectrum [41]. Figure 1.1, a Brainathlon screenshot, shows a composite wave and its filtered component frequencies. Figure 1.2 shows 2 channels of EEG activity separated into a spectrum [47].

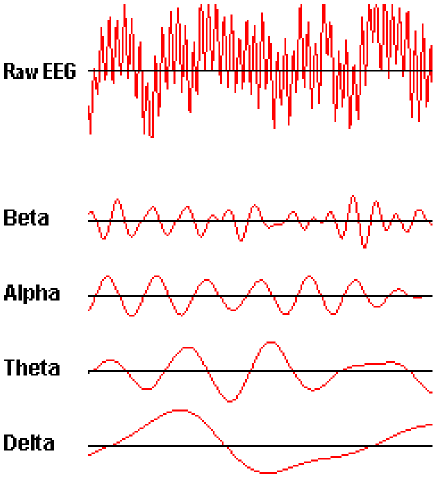


Figure 1.1: A raw EEG sample and its filtered component frequencies

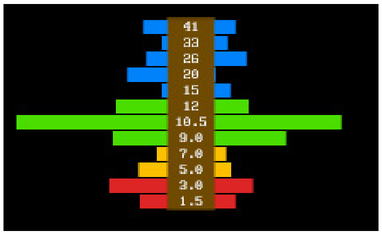


Figure 1.2: A 2 channel EEG spectrum display

1.3 History of the EEG

In the 1790's, Italian anatomist Luigi Galvani was dissecting a frog and discovered that a small electrical current caused the frog's leg to twitch [27]. This was the first demonstration that nerves conducted electrical impulses.

In the late 1920's, Hans Berger first recorded electrical activity in human scalps [27]. Berger discovered and named alpha and beta brainwaves, and he termed the recording of brainwaves *electroencephalograms*. The word was derived from a recording or tracing (gram) of the brain's (encephalo) electrical activity (electro). Initially scientists were skeptical of Berger's findings, and it took several years before his results were replicated and accepted by others.

In the mid 1960's, Barry Sterman was experimenting on cats at UCLA [23]. He identified the brainwaves associated with motor stillness, which he named sensorimotor rhythms (SMR). These waves are in the 12-15Hz range in cats. Sterman trained his cats to be still, which increased their SMR activity. He then found it was easier to encourage cats towards stillness by rewarding the appropriate brain activity rather than encouraging them to change their motor behavior directly. His cats became skilled at controlling their brain activity and increasing SMR waves.

Sterman then took on a research project for NASA, studying the toxic effects of a rocket fuel (monomethylhydrazine) which was known to cause seizures in humans. As he studied the effects of the fuel on his cats, he noticed that some of the cats had a much higher threshold for seizures than others. Strangely, the cats that were able to resist seizures were the same cats he had trained to produce SMR. This discovery launched a new field of EEG neurofeedback used to treat epilepsy, learning disabilities, hyperactivity, brain injury, and a range of other conditions.

1.4 EEG-Based Brain-Controlled Applications

Since the arrival of personal computing in the 1970's, people have been creating EEG-based input devices for computers [16]. The first applications simply displayed brainwave activity, as available computing power severely limited real-time analysis of brainwaves. With the increase in computing power, increasingly sophisticated applications have been developed for a variety of purposes, such as neurofeedback, assistive technology, art, and entertainment.

1.4.1 Early Neurofeedback

Biofeedback is a technique that teaches people to control physiological processes that are typically involuntary. Instruments (such as heart rate monitors, blood pressure gauges, or EEG devices) monitor physiological changes and "feed back" this information to the person being monitored. This allows individuals to extend their understanding of the process, and through training and practice, eventually gain some amount of conscious control over the process. Biofeedback to gain control over brainwave activity is called neurofeedback.

Joe Kamiya was the first researcher to demonstrate that human subjects could learn to consciously control their brainwaves when provided with feedback on their brain activity [10][32]. In the early 1960's, his subjects learned to increase and decrease alpha activity with the aid of an aural feedback tone that sounded whenever alpha activity was dominant. Although his subjects became proficient at both increasing and decreasing their alpha waves, they reported to greatly prefer increasing them, which they found to be peaceful and relaxing.

In this same time period, EEG studies of Yogis and Zen Masters showed that high levels of alpha activity were seen during meditation [2][33]. These experienced meditators also seemed to have elevated alpha levels during their normal resting state. Zen meditation, called Zazen, is practiced with the eyes open, so the increase in alpha cannot be attributed to closed eyes.

Since then, many studies have found that learning to increase alpha activity has numerous benefits such as decreasing anxiety, improving attention, and enhancing cognitive functioning [43][26]. However, other studies have found that these benefits were a result of perceived success in mastering a new activity and not actually a result of alpha activity [51]. Exaggerated promises of a "Nirvana state" and some early negative findings created skepticism and a loss of interest in neurofeedback [10]. But despite its fall from the public spotlight in the 1970's, a few researchers carried on with their neurofeedback studies, and the field has seen a revival in recent years.

1.4.2 Clinical Neurofeedback

EEG studies show that many medical and psychological disorders correlate with specific types of abnormal brain activity [13]. For example, alcoholism is associated with deficient alpha (8-12Hz) activity, and ADHD subjects typically have increased theta (4-8Hz) and decreased beta (12-20Hz) levels compared to the norm [14][39][45].

Neurofeedback researchers believe that, in many cases, these disorders can be treated using neurofeedback to retrain the patient's brain to match "normal" states of brain functioning. Clinical psychologists have had high success rates using neurofeedback to treat a wide variety of conditions from alcoholism to Attention Deficit Hyperactivity Disorder (ADHD) [14][55][45].

In 1989, Eugene Peniston and Paul Kulkosky published a study of their alpha-theta training protocol for treating alcoholism. All of the subjects had been battling alcoholism for over 20 years and had been through several unsuccessful rehabilitation treatments. After neurofeedback treatment, the treatment group experienced a significant decrease in self-assessed depression, and a 2 year follow-up showed that 8 of the 10 remained abstinent, while all 10 of the subjects in the control group had been rehospitalized [45]. Ellen Saxby and Eugene Peniston repeated the protocol in a 1995 study. Again subjects reported a significant decrease in depression, and in a 21 month follow-up, only 1 of the 14 subjects had relapsed [53].

Over the past 15 years there has been growing interest in neurofeedback treatment for attention problems and hyperactivity. Some neurofeedback clinics have success rates of up to 70-90%, which is higher than the 60-75% success rate of medications [36]. In recent years, various techniques have been used to make training easier and more interesting. Computer games, such as a variation of Pac-Man, have been developed to reward changes in brainwave activity. Current research in this area is focused on creating interesting, immersive applications, such as virtual reality environments [14].

1.4.3 Peak Performance Training

Neurofeedback is also used on healthy individuals in what is known as "peak performance training". Certain types of brain activity noted in athletes, highly creative individuals, and other "peak performers" are used as targets, and practitioners train to replicate the brain behavior of a golf pro or creative scientist.

Tonic (continuous) alpha power has been linked to increased memory performance and IQ [19][35]. Subjects with higher levels of tonic alpha activity tend to outperform those with lower levels. Sports scientists have noted bursts of alpha activity in expert golfers and archers immediately before swinging their golf club or shooting an arrow [43]. These findings have led peak performance specialists to recommend alpha training for a wide range of purposes including: improving accuracy and performance under pressure in golfers; increasing concentration and alertness in pilots and truck drivers; and enhancing problem solving, creativity and the ability to handle heavy workloads in students [43][24].

1.4.4 Augmentative and Alternative Communication

One particularly compelling application of EEG technology is in creating computer interfaces for severely disabled people. There are a number of alternative input devices for computers, such as voice recognition, head and eye-tracking devices, "sip and puff" switches, etc., but the use of these is limited to those with sufficient muscle control.

Some researchers have been working on brain-controlled interfaces that can be used by subjects who have little control over their bodies. In several studies, subjects who had previously been classified as being in a coma or "persistent vegetative state" were able to control a computer in order to interact and communicate with others [30][18]. As a result of these experiments, the classifications were removed.

Existing brain-controlled interfaces are effective, but users often require weeks of training to master the device. Current research in this area is focusing on using neural networks and pattern recognition algorithms so that the computer can adapt to the user, rather than requiring the user to learn biofeedback techniques to effectively use the interface [46][40].

In addition to controlling computers, people may soon have the ability to operate prosthetic limbs with the use of an EEG interface. Researchers at the University of Technology Graz in Austria have recently created an EEG controlled prosthetic hand that a quadriplegic user was able to control by simply imagining hand movements [49]. The patient has severe paralysis in all extremities except for his left bicep muscle. The device allowed him to grasp items with his left hand via imagined motor movement. After 4 months of training, he attained 100% accuracy with the device.

1.4.5 Art and Music

A few artists, such as David Rosenboom, have been experimenting with using EEG output to create or enhance performance art and music. In the 1970's, Rosenboom began using biofeedback devices such as EEG to allow performers to create sounds and music using their own brainwaves [52]. In his 1973 installation, Vancouver Piece, a pair of participants would see their faces superimposed on each other's bodies whenever their brainwaves were in phase with one another. In a later piece, On Being Invisible (1976–1977), an EEG device monitors a performer's brainwave activity, creating a dynamic musical composition.

Swedish artist Ola Persson used an EEG with plants in her "Yucca Invest Trading Plant" project [28]. In this art project, she attached electrodes to yucca palms and used a computer program that buys and sells stock according to each plant's wave activity. Although plants do not have brains, they do emit wave activity in the low delta range, similar to waves that people emit while in deep sleep or in a coma. Interacting with the plants provides a stimulus that affects the wave activity, causing the plant to buy or sell stock. One of Persson's yucca palms was quite successful in the stock market, reportedly outperforming index funds.

Current research using EEGs to create music attempts to move beyond simple associations between particular brainwave frequencies and particular sounds or actions. A group of music researchers has recently created a "Musical braincap," which uses EEG to detect active and passive listening, allowing the user to orchestrate and create music based on his or her brain state [41]. While actively listening to a musical passage, Eduardo Reck Miranda's application will create new music imitating the pattern of the current passage. This allows the musician to play a musical "solo".

1.4.6 Biofeedback Entertainment

The use of biofeedback games for pure entertainment has been uncommon. While many games have been created for biofeedback, most of these games are designed to provide psychological or medical treatment and are meant to be played only with the advice of a medical practitioner.

In 2002, a Swedish research firm called The Interactive Institute created an EEG based brain-controlled game for entertainment purposes [28]. In this game, players compete to out-relax each other. The game, called Brainball, involves two players sitting face to face across a table containing a metal ball in the center. As one player relaxes, the ball moves away from the player towards the opponent. Both players then compete to become more relaxed. The game is won when the ball is moved all the way across the table to the losing player. A commercial version of Brainball, called Mindball, was recently released costing approximately $19,000 for the standard version or $32,000 for the luxury version, which includes a pair of leather chairs [29].

Another commercial biofeedback game was released in late 2003. The game, "The Journey to Wild Divine," does not monitor brain activity or use an EEG; instead it monitors skin conductance level (SCL) and heart rate variability (HRV) [59]. SCL is a measure of sweat gland activity that is associated with the level of arousal of your sympathetic nervous system. As you become more alert or nervous, your level will increase, and as you become more mentally and physically relaxed, your level generally decreases. HRV is the difference in heart rate from one heartbeat to the next. Parts of the game encourage players to relax deeply by rewarding a decrease in SCL. Other parts of the game encourage players to raise their energy levels by rewarding increased heart rate or pulse strength.

1.5 Conclusion

With each passing year, increasing computing power increases the possibilities for EEG applications. Complex wave analysis can be performed in real-time, and artificial intelligence techniques are enhancing the computer's ability to associate a particular person's brain activity with a particular intention.

There has also been a growing interest in techniques for boosting health and happiness. Individuals flock to yoga classes, massage therapy and meditation retreats, hoping to improve their well-being. Affordable neurofeedback applications could provide people with a new tool for self-awareness and have the potential for teaching us new techniques for better managing the trials of our everyday lives.

Chapter 2

The Brainathlon Project

The range of useful tools being created with EEG-based brain-computer interfaces inspired the development of Brainathlon. The objective of the Brainathlon project was to design and develop an entertaining neurofeedback software application that could be used to develop self-awareness, and the goal was to make the application easy to configure and use.

2.1 EEG Devices

In order to use or build an EEG-based brain-controlled application, one must have access to a device that monitors brainwaves. However, the cost of such devices often places the development and use of these application out of reach for novice or experimental use.

2.1.1 Commercial EEG Devices

With the rise of EEG use in assistive technology, treatment of medical disorders, and peak performance training, there has been an increase in the number and variety of commercially available EEG devices for brain-computer input. A comprehensive review of these devices is out of the scope of this paper, but the following paragraphs provide an overview of two available devices.

Cyberlink

The Cyberlink System is one commercially available device that is used as an assistive technology tool. The system uses EEG monitoring combined with electrooculograph (EOG) monitoring of eye movements and electromyograph (EMG) monitoring of muscle activity in the forehead [7]. The system includes software that allows its users to control a computer completely hands-free, along with training software that helps users to learn to control the system. A software developers kit (SDK) can be purchased separately so programmers can create their own software applications for use with the Cyberlink EEG device.

This system has been the central tool for many remarkable success stories. Many of its users were completely unable to communicate prior to using the system and are now able to communicate with others as well as play games, perform research, write programs, and do almost anything that is possible with a computer.

The price of the Cyberlink System is just over $2000, and the SDK is an additional $350. While not unreasonably priced for a complete system, the cost is out of reach for researchers with limited funding.

BrainMaster

The BrainMaster 2 channel EEG system includes an EEG monitor and several software applications designed for neurofeedback [8]. It also includes software interfaces that allow programmers to develop their own applications for use with the device. Although the system is FDA approved for biofeedback training only under the supervision of a neurofeedback clinician, it can be purchased and used for non-clinical use. This system is sold through various distributors for approximately $1200.

2.1.2 An EEG Device For The Rest of Us – ModularEEG

An alternative to purchasing a commercial device is to build one yourself, and there has been a long history of do-it-yourself EEG device building projects. Steve Ciarcia, of Byte Magazine's *Ciarcia's Circuit Cellar* fame, may have been the first to expose do-it-yourselfers to EEG device creation. In the late 1970's, his "Mind Over Matter" article provided detailed plans and code for building an EEG input device [16]. Ciarcia expanded on this in 1988 with his HAL project described in the "Computers on the Brain" article [15].

In 2000, a small group of EEG enthusiasts formed an open source project named OpenEEG. With hardware specifications and source code, the project allows people to build their own brain-computer input devices. The project's tag line is *EEG for the rest of us*, indicating their intent to bring low cost EEG brain-computer interfaces to the hobbyist. This group recently coordinated with a parts manufacturer to provide pre-made circuit boards for their project [11].

The EEG device, called ModularEEG, can be built for approximately $200–$400, and if pre-assembled circuit boards are used, the system can be built by someone with limited electronic experience. All that is required is the ability to read a schematic, use a soldering iron, and track down the few parts required to put everything together.

The available commercial devices were out of budgetary reach given this project's limit of $500 in funding, so a ModularEEG device was built and used for Brainathlon. Since this project was benefiting from the hard work of the OpenEEG participants who designed the device, the software created for Brainathlon has been developed as open source to give back to the OpenEEG project.

2.2 Existing Software for the ModularEEG Device

The OpenEEG project's open, collaborative approach creates a perfect opportunity for student researchers to contribute to ongoing EEG application development.

Although there are several software applications written to work with the ModularEEG device, none of these applications contain libraries or code modules that were designed for reuse. This means that the low level work of EEG acquisition and analysis is implemented independently in each application, and that future applications would also need to have their own EEG acquisition and analysis code.

Although the ModularEEG device could be used for many types of applications, all of the current applications are designed for neurofeedback training.

2.3 Brainathlon Software

2.3.1 Development Objectives

The goal of this project was to create a different type of application for the ModularEEG device. In the spirit of Brainball, a competitive neurofeedback game would be designed and developed.

In addition to a software game, the aim was to build a reusable library of EEG acquisition and analysis components that could be used to build other applications for use with the ModularEEG device. The game application would also be designed to be easily extended if other programmers wanted to create different neurofeedback games.

Since the OpenEEG participants use a variety of platforms, including Linux, Windows, and Mac, it was decided that developing a cross-platform application would provide the most utility. Another project goal was to allow the game to be easily configured and used by non-technical people.

2.3.2 The Reusable EEG Acquisition and Analysis Libraries

One component of Brainathlon is a set of reusable libraries for monitoring, filtering, and analyzing EEG activity detected by the ModularEEG device. An EEG data acquisition library provides components that read the incoming data from the ModularEEG device and pass the raw EEG data along to interested software components. An EEG analysis library provides components that filter the raw EEG signal into its component frequencies and calculate wave amplitudes. The analysis library works in conjunction with a filter design library that contains digital signal processing components for creating filters that extract component frequency bands from a raw EEG signal. These libraries can be used together or separately to create future software applications designed for neurofeedback, entertainment, or some other purpose.

2.3.3 The Game

The Brainathlon game is a configurable software game that uses the OpenEEG project's ModularEEG hardware device to control game play. A single player can play the game alone, or two players can compete against one another to determine who is the better master of their own mind.

Players monitor and adjust their brainwave activity to control game UI elements, scoring points when their brain activity is within configured goal ranges. When sufficient points have been earned, the player wins the game.

Users can customize the game to encourage brainwave activity in their ranges of choice. This allows people who are currently being treated by a clinical neuropsychologist to configure the game for home training. It also allows people who want to experiment with brainwave control to configure the game however they'd like, creating a game that combines entertainment with the pursuit of self-knowledge.

This form of neurofeedback can help players identify their states of consciousness and train themselves to gain better control over their ability to concentrate, relax, and engage in creative thought. The software has a fun, game format, encouraging people to try it out and play on a regular basis. In addition, two players can play the game simultaneously, so it is an activity that can be shared with a friend or family member.

2.4 Contribution

A summary of the contributions of this research are as follows:

- A set of reusable, cross-platform libraries to aid in the creation of brain-interface applications for the ModularEEG device. These libraries provide a toolset for EEG acquisition and analysis, and they supply a framework for the addition of new analysis components created in future development.

- A configurable game for one or two players that encourages brainwave activity in user-specified frequency ranges. The game is designed to be easily customized and used by non-programmers.

Chapter 3

Implementation

The Brainathlon project was designed to meet the goals of portability, reusability, and configurability. Brainathlon was developed in Java to provide portability to the common operating systems. In addition to designing components for reuse, the project made use of the OpenEEG project's NeuroServer application, a TCP server that connects to the computer's serial port, reads the incoming ModularEEG data, and packages the data as TCP packets [17]. A diagram of the Brainathlon project's high-level design is shown in Figure 3.1. Figure 3.2 shows two players connected to the ModularEEG device and playing the Brainathlon game.

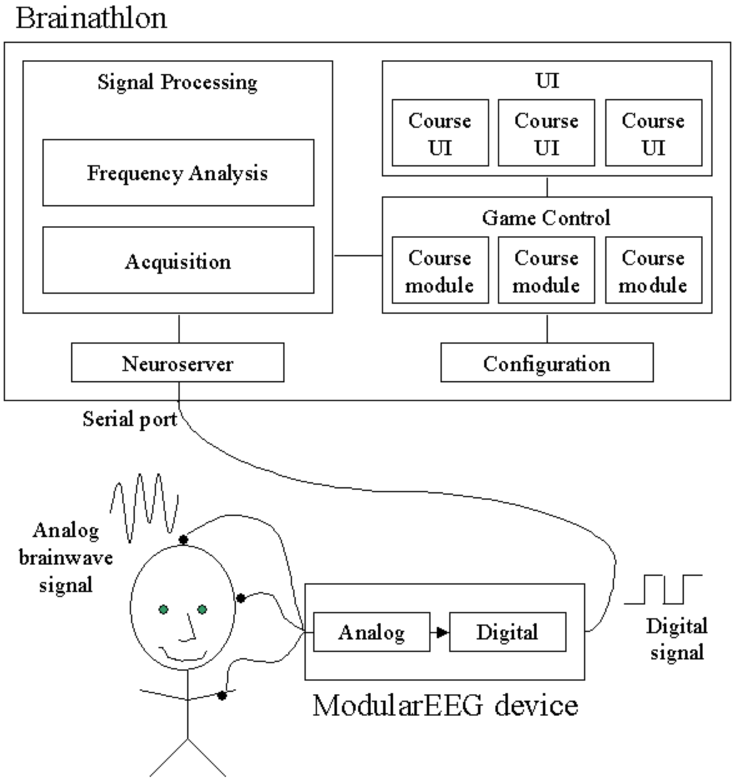


Figure 3.1: Brainathlon Design

Figure 3.2: Two Brainathlon players connected to the ModularEEG device

3.1 Hardware

3.1.1 EEG Monitoring Device

The EEG device used in Brainathlon is based on the OpenEEG project's ModularEEG design. This device provides the game's brain-computer hardware interface. The ModularEEG sends raw brainwave activity from attached electrodes into the computer's serial port.

ModularEEG Design

The ModularEEG device has two active channels, each with a reference channel, and one body ground used to cancel ambient electrical noise, such as 60Hz "mains hum" from power lines. The difference between the electrical activity captured by the active electrode and its reference electrode is the brainwave activity. To create the two-player game, each player has an active electrode attached to her head, a reference electrode attached to her ear, and a body ground electrode attached to her arm. Internally, the two players' body ground signals are linked and fed into one ground input on the ModularEEG amplifier board.

The ModularEEG device contains two electronics boards: an amplifier board and a digital board. The brainwave signal captured by the electrodes is very small and must be amplified. The amplifier board amplifies the signal and filters out much of the unwanted noise using a lowpass filter. Figure 3.3 shows a block diagram of the ModularEEG amplifier.

The digital board contains a microchip that is programmed to convert the signal from analog to digital, sampling it at the rate of 256 times a second. By Nyquist's theorem, the sampling rate must be at least twice the value of the highest component frequency in the signal. Since most EEG devices monitor brainwave activity between 1 and 50Hz, a sample rate of 256Hz should be sufficient to accurately detect brainwave activity without aliasing. After turning the signal into a stream of digital samples, the digital board sends the digitized output to a serial port. A diagram of the microcontroller is contained in Figure 3.4.

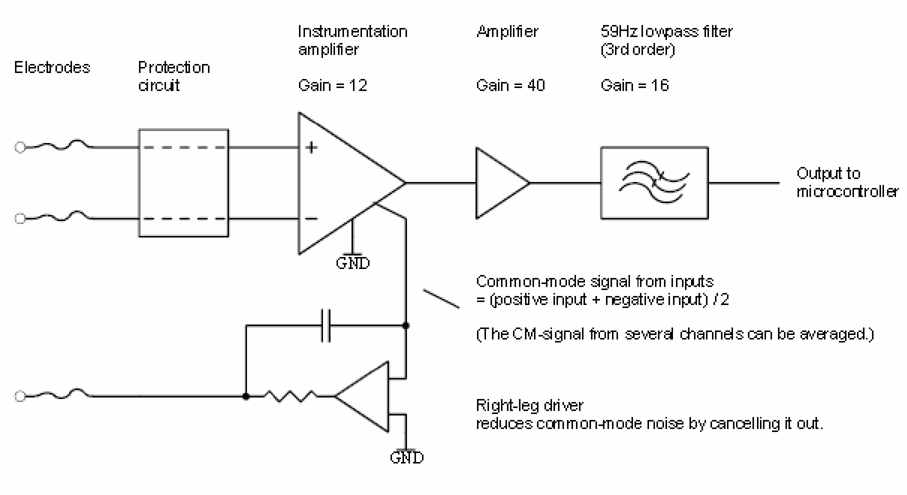


Figure 3.3: Simplified block diagram of the ModularEEG amplifier (from the OpenEEG website [11])

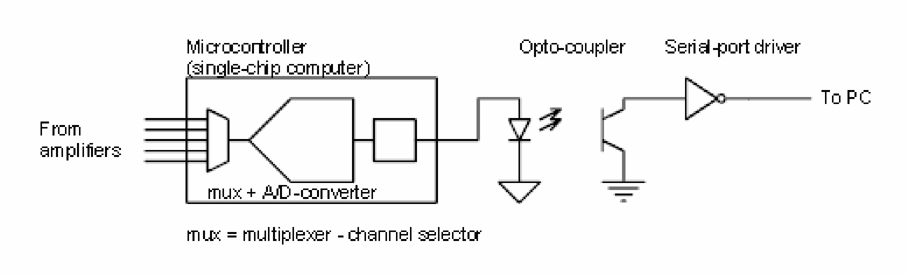


Figure 3.4: Simplified block diagram of the ModularEEG microcontroller (from the OpenEEG website [11])

Assembly

Pre-assembled electronics boards were purchased from Olimex, an electronics supply company located in Bulgaria. Using designs from OpenEEG project, cables and electrodes were built with parts from a local electronics shop. The amplifier board was enclosed in a metal box to reduce noise. The amplifier board's metal box was then enclosed in a plastic box along with the digital board. The two boards are shown in Figure 3.5, and the inside of the assembled ModularEEG device is shown in Figure 3.6. Figure 3.7 shows the fully assembled ModularEEG device.

3.1.2 Electrodes

The electrodes were constructed using detachable electrode discs and disc plugs purchased from The Electrode Store. The electrode plugs are attached to shielded audio cables which plug into RCA sockets that were mounted on the front that ModularEEG's plastic housing. For the reference electrodes to be placed on the ear, clip-on earring bases were attached to the disc plugs to create ear clips.

The electrodes are attached to the game players using conductive electrode paste. Athletic sweat

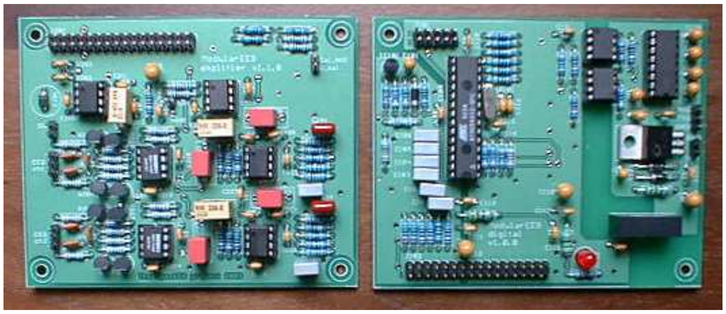


Figure 3.5: The pre-assembled boards

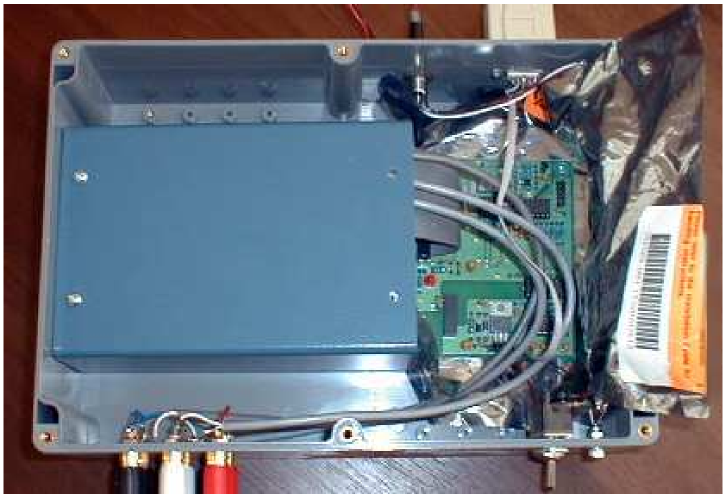


Figure 3.6: Inside the ModularEEG device

Figure 3.7: The completed ModularEEG device

bands hold the electrode cables around the players' heads and arms. The detachable discs allow for easy removal and clean-up of the paste-covered electrodes.

3.1.3 Imperfections

Despite the shielding on the electrode cables and the filtering in the ModularEEG's amplifier board, the device does pick up some 60Hz power line activity. This activity, often called "mains hum", is the 60Hz alternating current activity from the power lines that flow through the walls in our homes, schools, and offices. This residual hum is not a problem for the Brainathlon game, as the game's digital filters filter out the high frequency components of the signal.

Any physical movement can cause "noise" that is detected by the electrodes and interpreted as brain activity by Brainathlon. For example, teeth clenching, sneezing, laughing, and head movements can cause noise that is misinterpreted as a spike of high amplitude brain activity. Many EEG devices also contain muscle detection devices that are used to detect and cancel this type of noise. The ModularEEG device does not contain this sort of detection, so subjects need to remain very still for an accurate reading.

3.2 Software

The Brainathlon software is divided into several different layers. A signal processing layer handles the acquisition of the EEG signal and the analysis required to filter target frequencies that the game will monitor. Game control components handle the game play, scoring, and rewarding of the players' brain activity. The visual and audio display of the game activity is handled by the user interface (UI) layer. Figure 3.8 shows the Brainathlon software component layers.

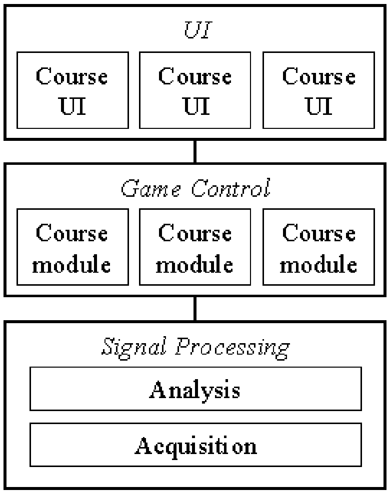


Figure 3.8: Brainathlon Layers

Since the application is based around EEG activity, the following description of the software components uses a bottom-up approach. It begins with a description of the EEG acquisition components, and then describes how the EEG signal is analyzed and used by the game control components. Next, the game logic is described for each of the three separate game courses, and it ends with a discussion of the UI and application logic components.

3.2.1 EEG Acquisition Components

NeuroServer

EEG input data is read into the computer using Rudi Cilibrasi's NeuroServer software [17]. NeuroServer is a TCP/IP server that reads incoming EEG data from the serial port and transfers the data wrapped in TCP packets. Applications can open a socket connection to the NeuroServer TCP port, and read the TCP packets. NeuroServer is cross-platform for Windows and Linux.

Java EEG Acquisition Library

An EEG acquisition library was created to read the TCP packets from NeuroServer and forward EEG input data to application components. A reader thread continuously reads incoming EEG data from a socket connection to NeuroServer. The reader packages up the sample data into a `Packet` object and forwards it on to its listeners. Figure 3.9 contains a class diagram of the major EEG acquisition components.

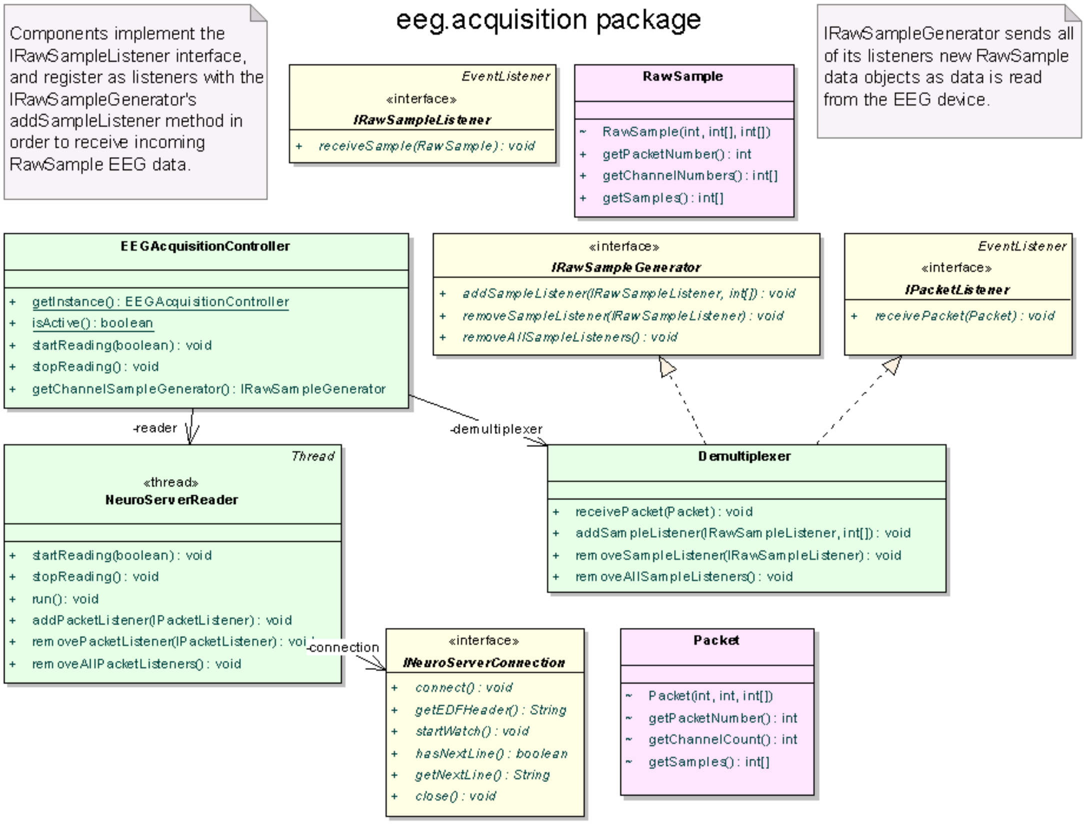


Figure 3.9: The EEG Acquisition Components

Both the EEG acquisition and EEG analysis libraries make heavy use of the *Observer* design pattern to notify components when new EEG data is acquired, filtered, and analyzed [22]. The Observer pattern is used to establish a relationship between an object that contains information and an object (or multiple objects) that require notification when the information changes. The observable subject maintains a list of observer objects, and notifies all of them when its state or information has changed. This is implemented using an interface which observer objects must implement.

By using interfaces, the Observer pattern allows the processing components to remain loosely coupled. This supports reuse, since future components can easily add themselves as listeners/observers to any of the processing components. This design also supports broadcast communication of the EEG data to all of the interested components. We are using the push model, where new data is always passed along to all registered listeners.

It is important to note that many of the EEG acquisition and analysis components have a dual role as both an observer and an observable subject. These components listen for new data, process it, and then notify their listeners with the new, processed information. This sets up a pipeline of processing components that allows other objects to tap into the data being produced from anywhere inside the pipeline. This allows for functionality such as a UI that can display a raw signal wave, a filtered wave, an average amplitude value, and a player's score simultaneously, all based on the same EEG data.

The application initializes the flow of EEG data by calling the `EEGAcquisitionController` object's `startReading` method, which in turn starts the `NeuroServerReader` thread. The `NeuroServerReader` thread reads EEG data from the ModularEEG device approximately 256 times per second and notifies the observing `Demultiplexer` object. The `Demultiplexer` (which implements `IRawSampleGenerator`) separates out the EEG channel data and sends the appropriate channel data to each of its listeners. Figure 3.10 shows a sequence diagram of the reader thread initialization.

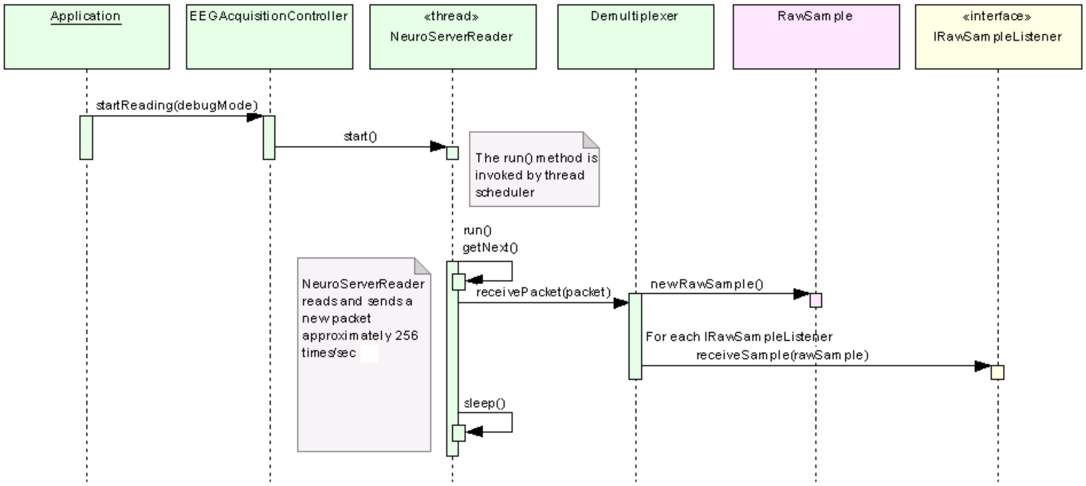


Figure 3.10: Sequence diagram showing the initialization of the reader thread

The `EEGAcquisitionController` object controls access to an observable raw sample generator (the `Demultiplexer` object). Application components that wish to receive incoming raw samples add themselves as listeners to the raw sample generator. Listener objects tell the raw sample generator which channel or channels they are interested in when they register as listeners. As new data is acquired, the generator demultiplexes the samples for each channel and sends `RawSample` objects to all of its registered listeners. `RawSample` objects contain sample data from one or more channels, along with the corresponding channel number. A sequence diagram showing the registration process is provided in Figure 3.11.

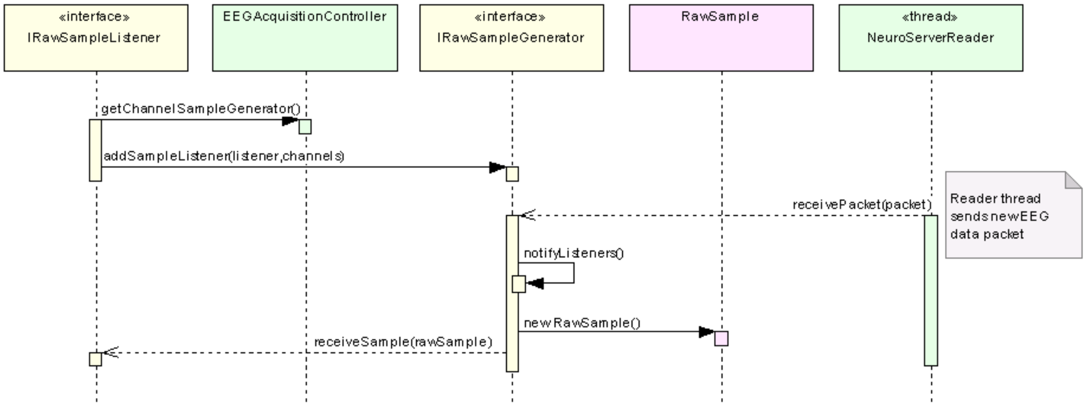


Figure 3.11: Sequence diagram showing registration and receiving of EEG data

3.2.2 EEG Analysis Components

Brainathlon contains several different types of analysis components. Filters isolate particular frequency bands from a raw composite signal. The filtered signal can then be analyzed by a monitor that calculates the signals average amplitude or strength. Game components analyze the average amplitude of the signal and reward increases to encourage brainwave activity in the frequency band.

Digital Filters

The raw signal output from the EEG device requires additional processing to provide useful information, as the signal contains the combined activity from all brainwave frequencies. In order to analyze the amount of brain activity in a particular frequency band, such as alpha (8-12 Hz), the activity in this frequency range must be separated out. Digital filters can be used to separate out the component frequency bands of the raw EEG output. Typical filtering techniques include Fast Fourier Transforms (FFT), Finite Impulse Response (FIR) filters, and Infinite Impulse Response (IIR) filters [38].

All three filtering techniques are used in neurofeedback applications, but IIR filters have some advantages that make them useful for our application. Both FIR and IIR filters use previous inputs along with the current input in order to calculate the current output [38]. As a result, a continuous stream of output is generated by providing the filter with a continuous stream of input. This is unlike a FFT filter which processes data in chunks. With this continuous stream of filtered data, it will be possible to monitor the data and note changes in real time. Since the Brainathlon application requires real-time monitoring of filtered data, impulse response filters were used.

IIR filters are recursive, meaning they use previous outputs as well as inputs when calculating current output values. Despite using additional data, IIR filters are very efficient and can calculate outputs with far fewer multiplications than a FIR filter. This means they can achieve good results with less memory and delay, making them suitable for real-time filtering. For this reason, IIR filters were chosen for the Brainathlon application.

Ideally, filters would provide a “brick wall,” meaning that all frequencies inside of the desired range would be passed through, and all frequencies outside of the range would be stopped. Unfortunately, it is not possible to build this ideal. Digital filters will always contain a transition between the passband (the frequency range which is passed through the filter) and the stopband (the frequency range that is blocked by the filter) where adjacent frequencies will pass. This transition is called roll-off, and the steeper the slope of this transition band, the closer the filter will approximate a brick wall filter. IIR filters are good at approximating the brick wall ideal. They have the sharpest roll-off with the least amount of inputs compared to FIR filters. But it is important to note that some amount of adjacent frequency data will be included in the filtered sample. Figure 3.12 shows the difference between the "brick wall" ideal and a real world filter with roll-off.

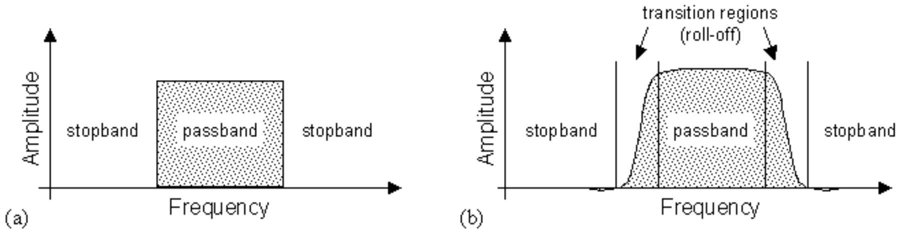


Figure 3.12: (a) A "brick wall" ideal bandpass filter. (b) A real world filter with roll-off . (Adapted from [38][20])

In an IIR filter, each input and output is multiplied by a coefficient to get a new output value. The number of inputs used by a recursive filter is called the filter order. A larger filter order will, in general, result in a better frequency response. A general equation for an Mth-order IIR filter is:

$$y_n = b_0(x_n) + b_1(x_{n-1}) + b_2(x_{n-2}) + ... + b_M(x_{n-M}) + a_1(y_{n-1}) + a_2(y_{n-2}) + ... + a_M(y_{n-M})$$

In this equation, y_n represents the nth output value. The series $b_0 - b_M$ represents the coefficients used with input values $x_n - x_{n-M}$, and the series $a_1 - a_M$ represents the coefficients used with previous output values $y_{n-1} - y_{n-M}$ [38].

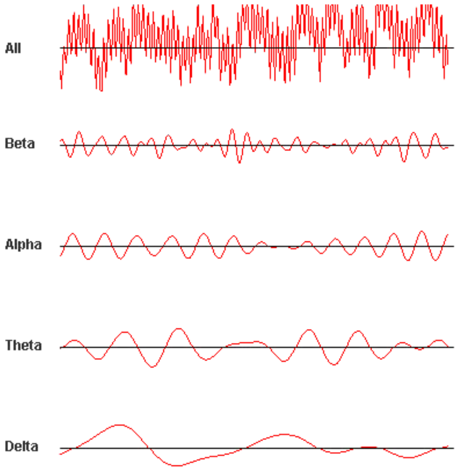


Figure 3.13: A raw EEG signal is filtered into its component frequencies

Figure 3.13, a screenshot from Brainathlon, demonstrates the use of filters. The raw EEG signal is displayed at the top, and the beta, alpha, theta, and delta component frequencies separated out by individual IIR filters.

Filter Algorithms

Some common filter functions are Butterworth, Bessel, and Chebyshev [20]. Butterworth filters were used for this project because they are maximally flat in the passband, meaning they have the smallest amount of ripple or fluctuation in passband response.

Filter Design Library

Brainathlon allows users to configure the games to encourage brain activity in user specified ranges. This requires IIR filters to be generated at runtime. During development, no suitable open source Java filter design library was found, but OpenEEG member Jim Peters has developed an open source C library for filter design [48]. The Brainathlon project ported portions of this C library to Java, creating a filter designer that can create Butterworth bandpass filters on the fly.

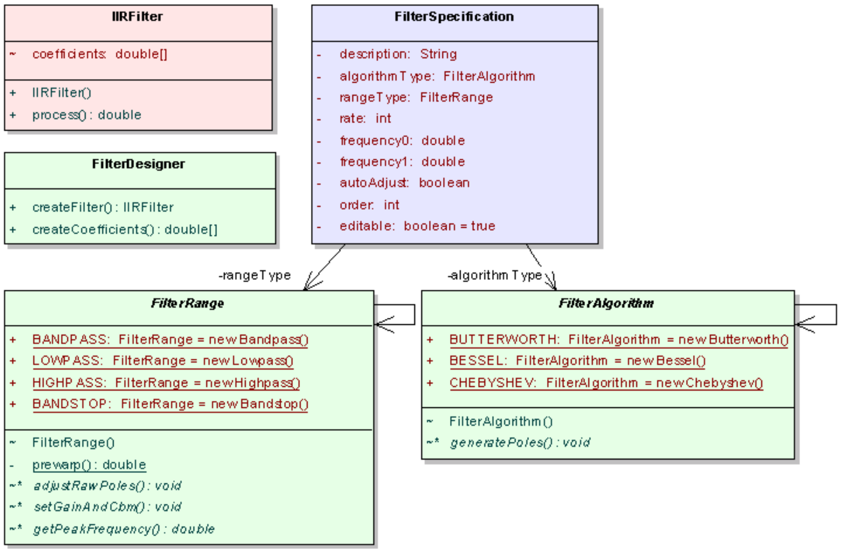


Figure 3.14: A class diagram showing the key components of the filter design library

Although only the portions of code that design bandpass filter range using the Butterworth function were ported, the library was designed to facilitate the porting of additional functionality. The *Strategy* pattern was used for the filter range and filter algorithm functionality [22]. In addition to the current bandpass code, the code that designs lowpass, highpass, and bandstop filters may be ported in the future. The filter range design functionality is encapsulated so that the currently implemented `FilterRange` code will be interchangeable with newly ported strategy code for the other ranges. The Bessel and Chebyshev filter design functions may also be ported in the future, so the `FilterAlgorithm` functionality was also designed to be encapsulated and interchangeable. The core components of the filter design library are shown in Figure 3.14.

The filter design library includes a `FilterDesigner` object that creates `IIRFilter` objects. The filters are designed according to specifications defined in a `FilterSpecification` object. A `FilterSpecification` contains the desired frequency range and filter order. Once an `IIRFilter` object is created, its `process` method can be used to filter raw wave input into output that contains filtered activity from the specified frequency band. Figure 3.15 illustrates the steps involved in creating a new IIR filter.

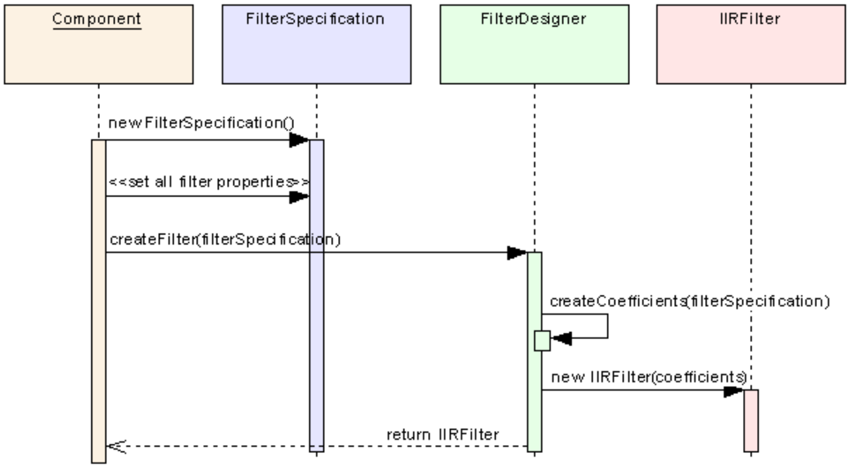


Figure 3.15: A sequence diagram demonstrating the creation of a new IIR filter

Brainathlon Filters

Brainathlon contains three different types of filters, each utilizing IIR filters to isolate the desired frequencies. `BandFilter` objects generate sample values for one frequency band. `DualBandFilter` objects generate two sample values, one for each of two frequency bands. This type of filter is useful when two frequency bands will be compared, such as in determining the ratio of activity from one frequency band to another. `SpectrumFilter` objects generate four sample values, one for each of the four standard frequency bands of beta, alpha, theta, and delta. `SpectrumFilter`s are useful when all four of the standard frequency bands are needed.

Both `BandFilter`s and `DualBandFilter`s can be designed to filter for any frequency range. Their constructors take `FilterSpecification` objects as parameters and design an `IIRFilter` on the fly. `SpectrumFilter`s are not configurable and use predefined frequency ranges.

Like the EEG acquisition processing components, the filters utilize the *Observable* pattern. Each filter is an observer of a particular EEG channel and is also observable, sending out filtered frequency band samples to all of its listeners. To use one of these filters, objects add themselves as listeners and then receive filtered samples as the filter object generates them.

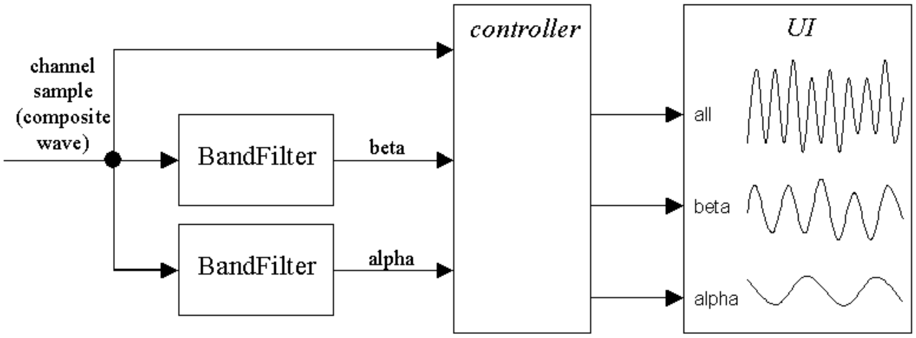


Figure 3.16: Two `BandFilter`s isolate frequency ranges from the original signal

Multiple filters can listen to the same signal and filter out different composite frequencies. Figure

3.16 illustrates the use of two `BandFilter`s used in parallel to display alpha and beta waves, along with the original composite wave.

Calculating Signal Amplitude

In order to monitor the brainwave power in a particular frequency band, the average amplitude of the wave must be calculated. Attempting to calculate the average amplitude of a wave by averaging all of the sample values would result in zero, since waves are commonly symmetrical above and below the midline. Therefore, signal power is typically calculated by taking the "root mean square" (RMS) value. This is the square root of the mean of each sample value squared, or:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}$$

The RMS value of a sine wave is approximately 70% of its peak amplitude (see Figure 3.17).

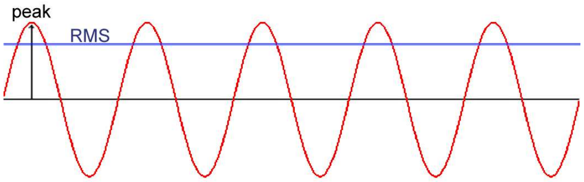


Figure 3.17: Root Mean Square (RMS) value of a sine wave

Since RMS calculates the average power, when the power of the wave is fluctuating, the number of samples used in the calculation will affect the resulting value. A small window of samples will capture small fluctuations in activity, and a large window will mask small fluctuations. For example, in Figure 3.18 a sample size of 32 would divide the wave into four segments with fluctuating RMS values of 9.1, 3.2, 5.8, and 9.1. A sample size of 64 would result in less fluctuation; the wave would be divided into two segments with RMS values of 6.8 and 7.6. A sample size of 128 would result in a single RMS value of 7.3 for this entire segment of the input wave.

Filter Monitors

Brainathlon contains several types of filter monitors that receive filtered samples and calculate amplitude values. The number of samples to use in the RMS amplitude calculations is specified in the constructor for each of the Brainathlon filter monitors.

A `BandMonitor` object calculates average amplitude values (using RMS) for a single filtered frequency band. Objects that need to monitor amplitude add themselves as listeners to the monitor and will receive the monitor's new amplitude calculations.

A `RatioMonitor` object calculates average amplitude values for two bands and then calculates the ratio of the first band to the second. As with the `BandMonitor`, objects that need to monitor amplitude ratios add themselves as listeners to the monitor and will receive the monitor's new ratio calculations.

Multiple filters and monitors work in parallel during Brainathlon game play. Each player's brainwave signal is filtered and monitored by separate objects, and a single game control object scores the game and updates the UI. Figure 3.19 demonstrates the use of multiple `BandFilter` and `BandMonitor` objects working to provide a game component with two players' average alpha amplitude. The game component can then track changes in each player's amplitude and use both the amplitude and amount of change to determine the player's score.

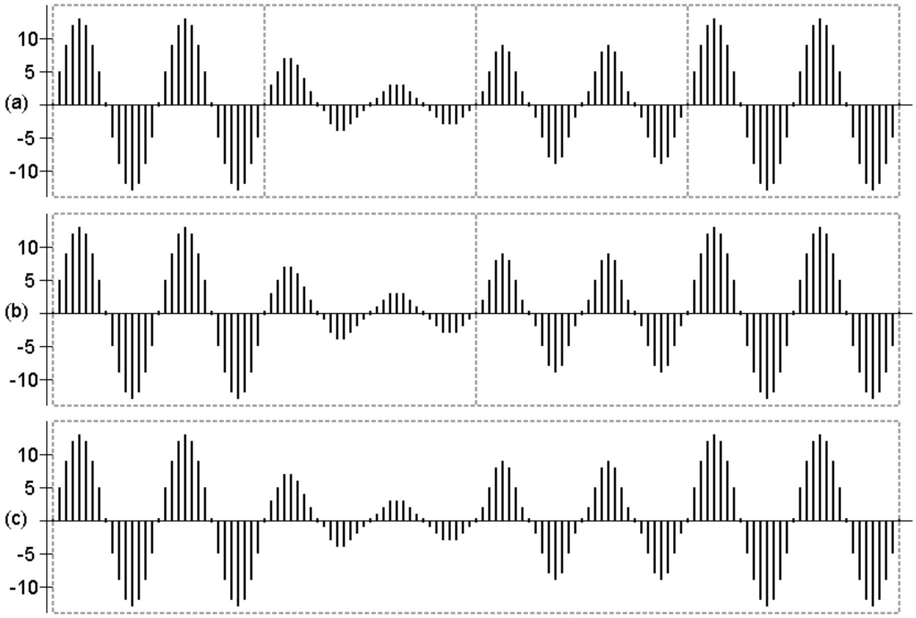


Figure 3.18: A fluctuating wave divided into windows of (a) 32 samples, (b) 64 samples and (c) 128 samples

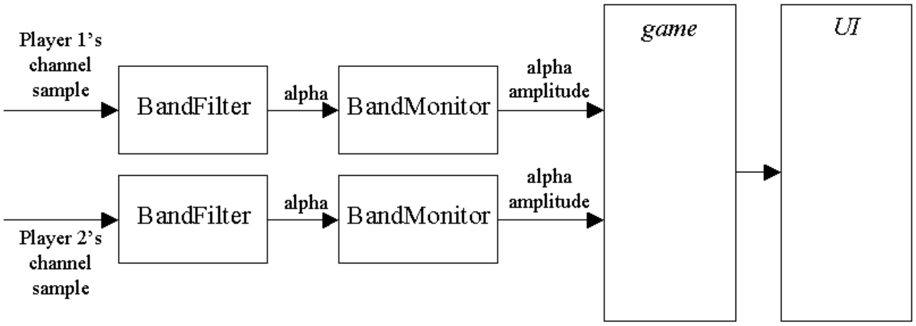


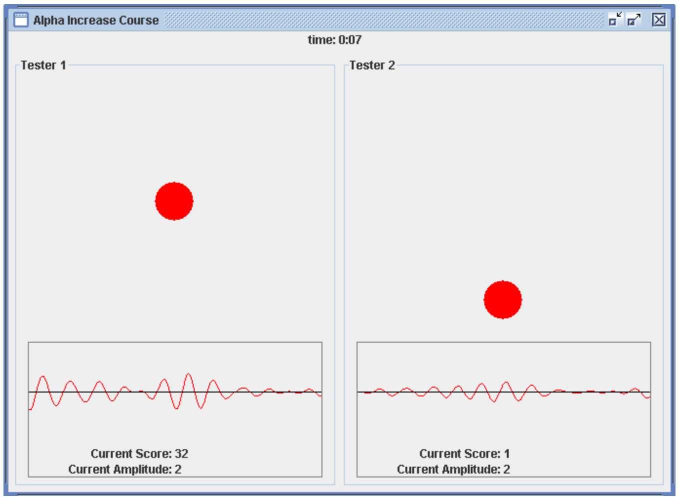
Figure 3.19: Two `BandFilter`s isolate frequency ranges from the original signal

3.2.3 The Game

The Brainathlon game consists of three consecutive mini-games called *courses*. Each course monitors and rewards activity in configurable brainwave ranges. The game can be played by one player or by two players simultaneously. When played in two-player mode, the player who wins the most events will win the game.

When the game is played by two players, the screen is split in half vertically with player 1's game board on the left and player 2's on the right, as shown in Figure 3.20. When a single player is playing, only one game board appears on the screen, as shown in Figure 3.21.

During all of the courses, a small display of current brainwave activity in the target frequency band is displayed at the bottom of the screen. This display provides additional feedback to the players and assists them in identifying increases and decreases in brain activity.


Alpha Increase Course

time: 0:07

Tester 1

Current Score: 32

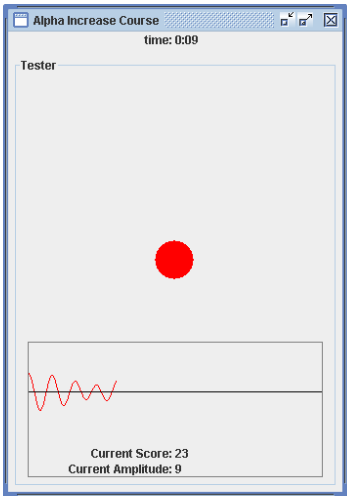
Current Amplitude: 2

Tester 2

Current Score: 1

Current Amplitude: 2

Figure 3.20: Two-player mode


Alpha Increase Course

time: 0:09

Tester

Current Score: 23

Current Amplitude: 9

Figure 3.21: One-player mode

Each course has an accompanying XML configuration file where users can set the frequency ranges, time limits, and other course variables. The configuration is read into the application at runtime, so changing the game to suit different players' training interests and skill levels is easy.

Figure 3.22 shows the central classes involved in the game logic. The shared logic for all courses is extracted into an `AbstractCourse` class. Logic specific to the individual courses is contained in concrete course classes. A `GameController` object contains a collection of course objects, and cycles through them during game play. The `GameController` class makes use of the *State* pattern to cycle through the different game lifecycle states [22]. The State pattern allows the `GameController` object to change its behavior based on its internal state. A class diagram of the `GameController` and its `GameState` inner classes is shown in Figure 3.23.

When the application begins, the `GameController` is in its `ReadyState`. In this state, the controller displays a dialog box that the user must click in order to begin the game. This places the controller in its `GameInProgressState`, which cycles through and begins each course. When all three courses are complete, the controller enters its `GameOverState`. This state displays a dialog with the final scores and returns control back to the main application component.

Course Logic and Data Flow

The individual courses are responsible for creating the data analysis components they require. Courses must also register each component as a listener with the other components along the EEG data flow pipeline. The `GameController` object passes a list of `Player` objects to the course constructor. Each `Player` object is linked to the EEG acquisition subsystem, listening for data on the player's input channel. Filters register as listeners with the `Player` objects, then monitors register as listeners with the filter objects. Figure 3.24 shows the sequence of method calls involved in setting up the data flow for the course.

Once the course has linked the components together, EEG data begins to flow through the game. The course components receive calculated amplitude values, which are scored according to the course's configuration. The current score, amplitude, and filtered sample values are all passed along to the course UI and displayed to the user. A sequence diagram showing the flow of data analysis is contained in Figure 3.25.

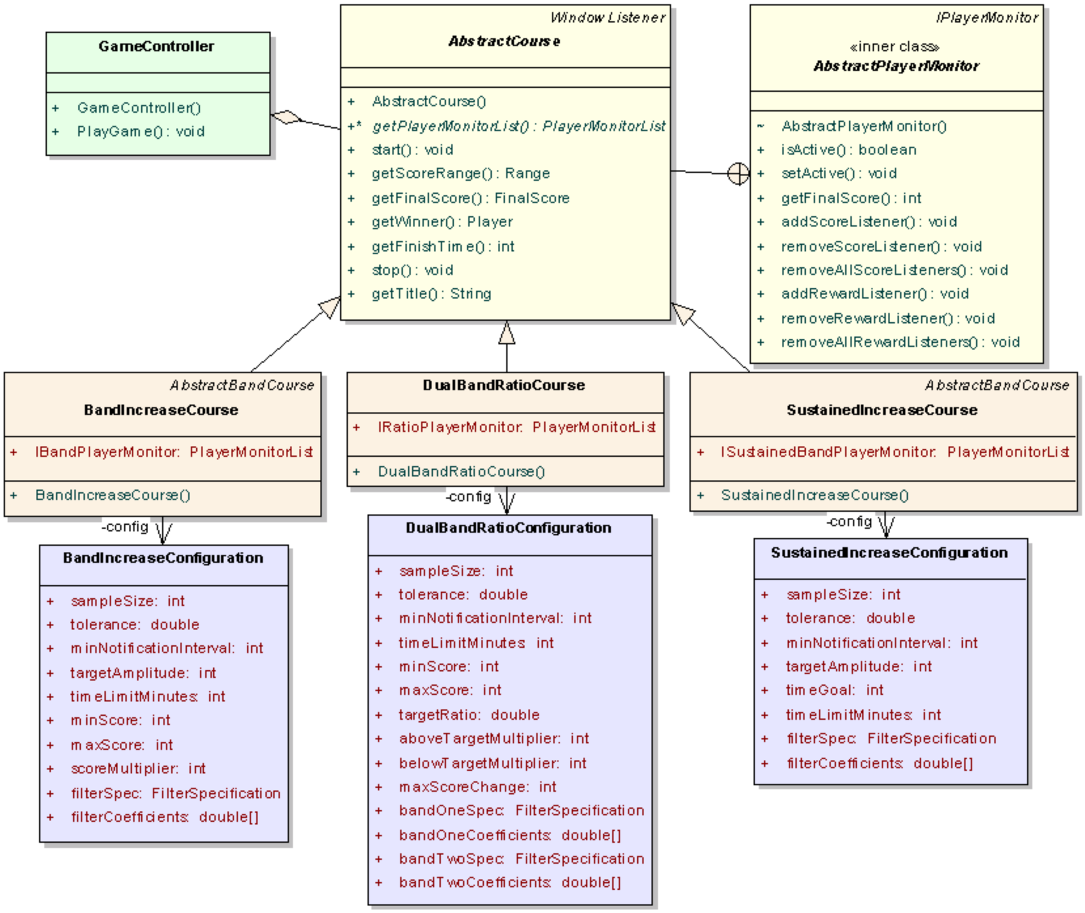


Figure 3.22: Class diagram of the key course components

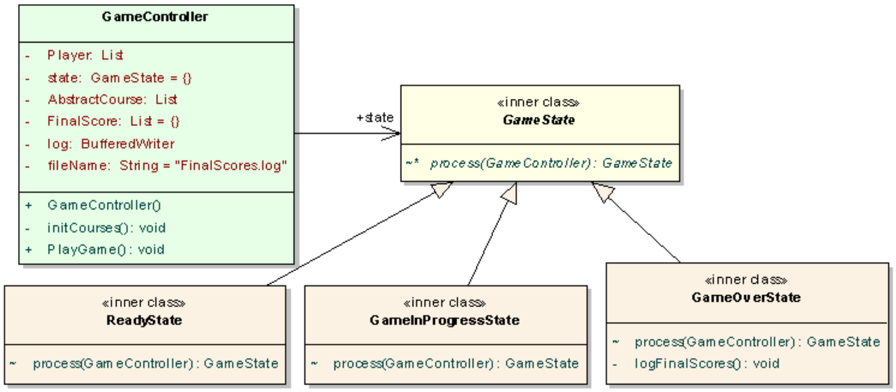
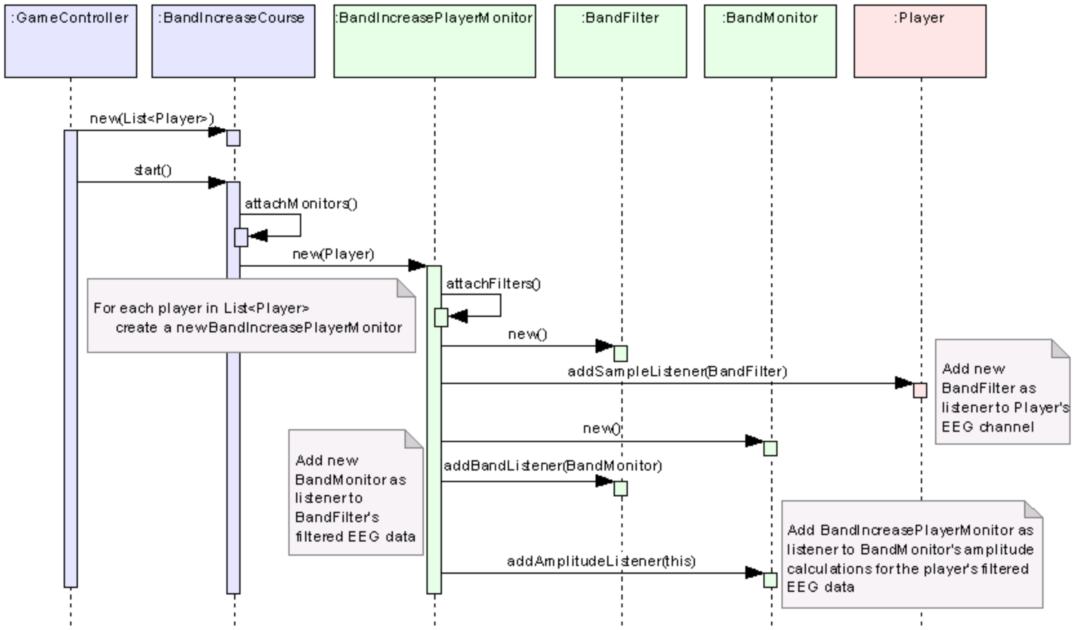


Figure 3.23: The `GameController` logic is handled by internal `GameStates`



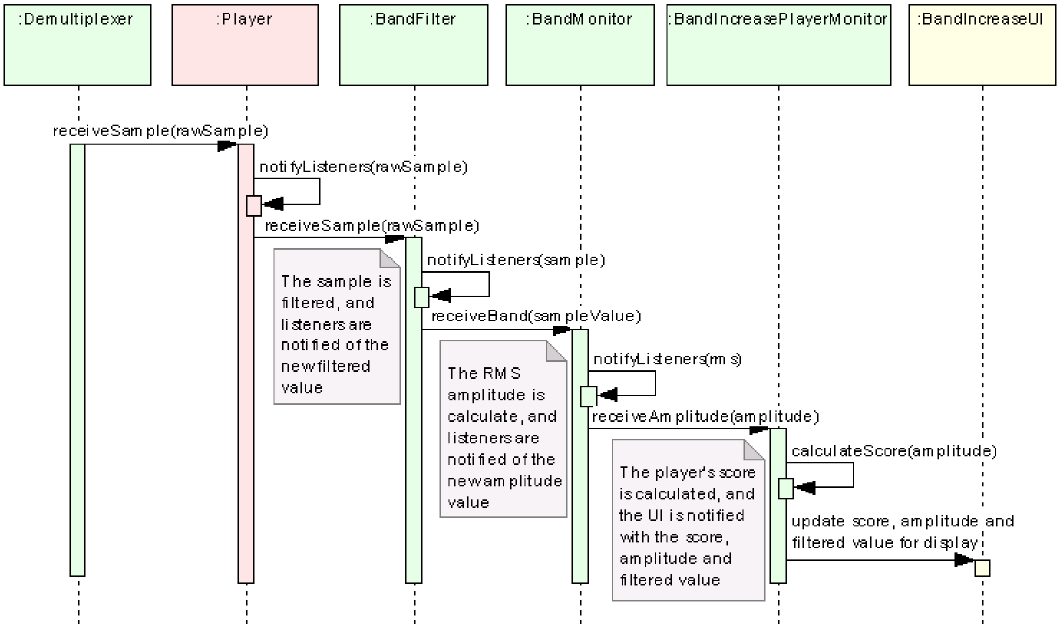
For each player in List<Player> create a new BandIncreasePlayerMonitor

Add new BandFilter as listener to Player's EEG channel

Add new BandMonitor as listener to BandFilter's filtered EEG data

Add BandIncreasePlayerMonitor as listener to BandMonitor's amplitude calculations for the player's filtered EEG data

Figure 3.24: Sequence diagram of course data flow set up



The sample is filtered, and listeners are notified of the new filtered value

The RMS amplitude is calculate, and listeners are notified of the new amplitude value

The player's score is calculated, and the UI is notified with the score, amplitude and filtered value

Figure 3.25: The flow of data and analysis through the Band Increase Course

User Interface Components

The user interface in Brainathlon consists of both graphics and sound. The Java Swing toolset is used to generate the game's graphics. The game also provides audio feedback using Java's Midi support. Midi supports playback of overlapping sounds and is cross-platform.

The UI components are implemented using a *Model-View-Controller* approach [60]. The course objects act as the Controller, setting up listener relationships between the EEG data (which assumes the role of Model) and the UI (View). The UI then receives data updates and displays the data to the user. EEG data flows all the way from the EEG reader component through to the UI components using a chain of *Observer* relationships. Figure 3.26 shows the flow of data all the way through the application.

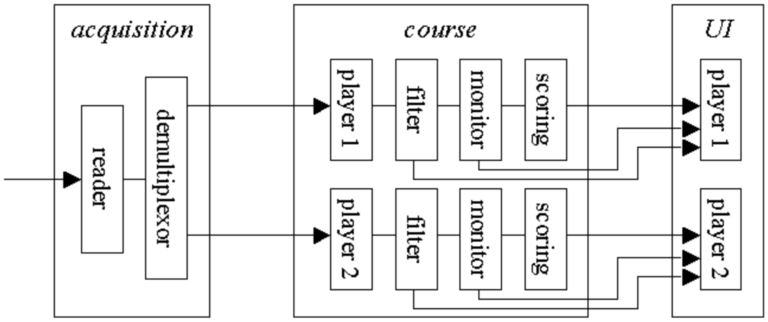


Figure 3.26: EEG data flows through the application via *Observer* relationships between components

Course #1 - Band Increase Course

Course #1, the "Band Increase Course", encourages high amplitude activity in a specified frequency range. The course begins with a red "ball" near the bottom of the screen and a horizontal "finish line" near the top. As a player's brain activity in the specified range increases, the ball moves up the screen. A decrease in activity moves the ball back down the screen. A screenshot of the course is shown in Figure 3.27.

When the activity level surpasses a configured target amplitude, the minimum height level of the ball is raised; if the activity level drops off, the ball will not fall further than the new minimum level. This allows the player to slowly inch towards the top with spikes of high level brain activity. Sustained high levels of activity will move the ball quickly to the top.

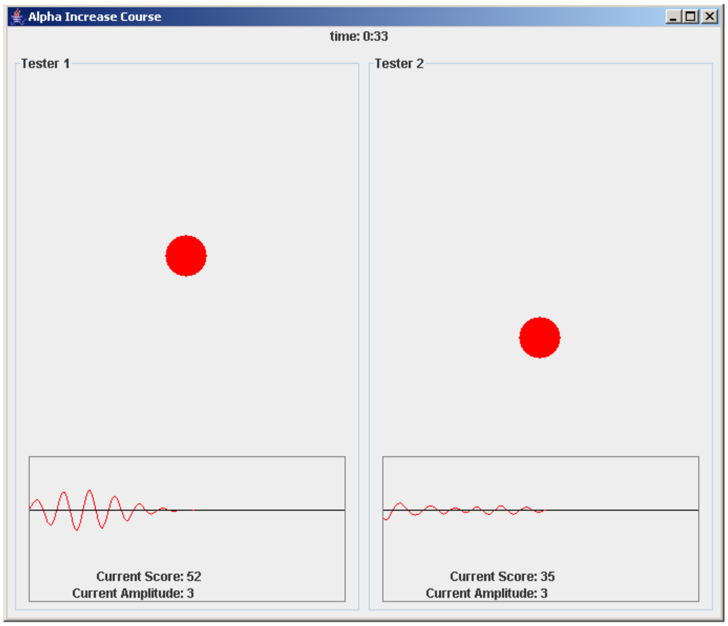
By rewarding momentary spikes of high amplitude activity, players are quickly able to identify and repeat the activity. In our testing, 10 out of 11 solo players were able to win this game, within the five minute limit, on their first try.

In two-player mode, the first player to raise her ball to the top of the screen wins the game. If neither player raises their ball to the top by the end of the configured time limit, the player who raised her ball the highest will win the course.

The frequency range, target amplitude, time limit, and scoring variables are all specified in the course's configuration file. This allows the course to be tailored to reward different frequency bands, and made more or less difficult.

Course #2 - Sustained Increase Course

Course #2, the "Sustained Increase Course" encourages sustained high level activity in a specified frequency band. It begins with a red square displayed at the center of the screen. The color of the square changes to green when the player's brain activity in the specified range surpasses a specified target amplitude. If the player's brain activity remains over the target, a timer begins counting down from a specified goal time with each second that the amplitude is sustained. A screenshot of this course is displayed in Figure 3.28.

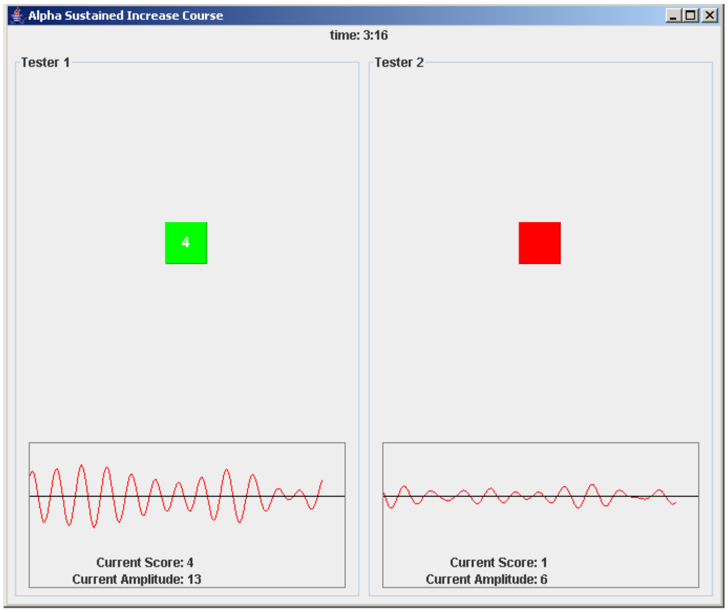


time: 0:33

Current Score: 52
Current Amplitude: 3

Current Score: 35
Current Amplitude: 3

Figure 3.27: Band Increase Course screenshot



time: 3:16

Current Score: 4
Current Amplitude: 13

Current Score: 1
Current Amplitude: 6

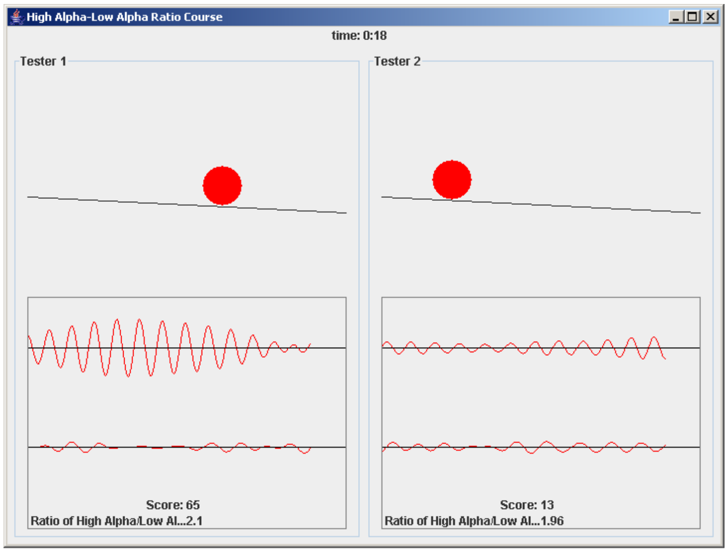
Figure 3.28: Sustained Increase Course screenshot

The player receives a point for each consecutive sustained second and wins the game when the timer reaches zero, indicating that the amplitude was sustained for the entire goal time. When playing in two-player mode, the player with the highest score wins if the time limit is reached before either player reaches the time goal.

The frequency range, target amplitude, goal time, and time limit are all specified in the course's configuration file. A player who becomes skilled at sustaining the target amplitude can increase the goal time to continue training.

Course #3 - Dual Band Ratio Course

Course #3 monitors activity in two different frequency bands, encouraging activity above a specified ratio of one band to the other. The course begins with a red "ball" in the center of the screen, balanced on top of a black line that extends from the left of the screen to the right of the screen. Figure 3.29 contains a screenshot of the course.



Score: 65
Ratio of High Alpha/Low Al...2.1

Score: 13
Ratio of High Alpha/Low Al...1.96

Figure 3.29: Dual Band Ratio Course screenshot

When the player's brain activity increases over the specified ratio, the line tilts and the ball rolls to the right. When the player's brain activity dips below the specified ratio, the line tilts in the opposite direction and the ball rolls to the left. The first player whose ball reaches the right side of the screen wins the game. If neither player reaches the right side before the time limit is up, the player whose ball made it the farthest to the right wins the game.

The two frequency ranges, target ratio, time limit, and scoring variables are all specified in the course's configuration file.

3.2.4 Configuration

One of the goals of the Brainathlon project was to create a game that could be configured and used by non-programmers. This is accomplished by using XML configuration files to control pieces of course logic, such as target frequency bands, sample size for RMS amplitude calculations, filter order, and time limit for each course. The XML files are accessed using the open source XStream library [56]. During application initialization, the XML files for each course are read and the values are used during course initialization.

Calculating filter coefficients is somewhat time consuming, so the coefficients are saved in the configuration file. If the user wishes to change any filter attributes, the saved coefficient values in the XML file must be deleted. When a course reads its configuration file and detects that the filter coefficients are missing, new coefficients will be calculated for the filter described in the XML file.

When the game exits, the new coefficients will be saved in the XML file. Figure 3.30 shows the configuration file for the Band Increase Course with saved filter coefficient values.

```
- <gameControl.BandIncreaseConfiguration>
    <sampleSize>64</sampleSize>
    <tolerance>2.0</tolerance>
    <minNotificationInterval>16</minNotificationInterval>
    <targetAmplitude>12</targetAmplitude>
    <timeLimitMinutes>5</timeLimitMinutes>
    <minScore>0</minScore>
    <maxScore>100</maxScore>
    <scoreMultiplier>2</scoreMultiplier>
  - <filterSpec>
      <description>Alpha</description>
    - <algorithmType class="filterdesign.FilterAlgorithm-Butterworth">
        <name>Butterworth</name>
      </algorithmType>
    - <rangeType class="filterdesign.FilterRange-Bandpass">
        <name>Bandpass</name>
      </rangeType>
      <rate>256</rate>
      <frequency0>8.0</frequency0>
      <frequency1>12.0</frequency1>
      <autoAdjust>true</autoAdjust>
      <order>5</order>
      <editable>false</editable>
    </filterSpec>
  - <filterCoefficients>
      <double>1.4328139213007392E-7</double>
      <double>0.9687692182991368</double>
      <double>-1.888780817710422</double>
      <double>0.9776675530769263</double>
      <double>-1.9373671043764888</double>
      <double>0.9242662416208486</double>
      <double>-1.8555126725577347</double>
      <double>0.9383360044218676</double>
      <double>-1.8933731982856097</double>
      <double>0.9156801402563697</double>
      <double>-1.8605106731373373</double>
    </filterCoefficients>
  </gameControl.BandIncreaseConfiguration>
```

Figure 3.30: The configuration file for the Band Increase Course

3.2.5 Application Logic

The entire game is controlled by an `Application` object. Like the `GameController`, the `Application` class uses the *State* pattern to cycle through application lifecycle states. A class diagram of the `Application` and its `ApplicationState` inner classes is shown in Figure 3.31.

3.2.6 The Development Process

The development of Brainathlon was completed in approximately three months time. Initial design was performed using *Class-Responsibility-Candidate* (CRC) cards to identify key components based on the application's required responsibilities [60]. CRC cards are simply index cards with names and responsibilities of candidate classes. When the roles, responsibilities, and collaborations for a subsystem were defined, the set of classes was implemented.

The development process began with an "architectural spike," where the EEG data pipeline was designed and developed. This was a full slice of the final application from data acquisition to user interface display. Implementing an architectural spike is a technique that can be used to rapidly design, implement, and test a crucial piece of application architecture. By constructing only a small slice of the application, it's possible to explore different options without requiring massive code changes. This process also provided a proof-of-concept, assuring that it would be possible to do real-time analysis of brainwave activity using Java and the ModularEEG device.

During this phase, the EEG acquisition components were created first, then the EEG analysis components, and finally a simple UI that displayed the raw signal and filtered component frequency

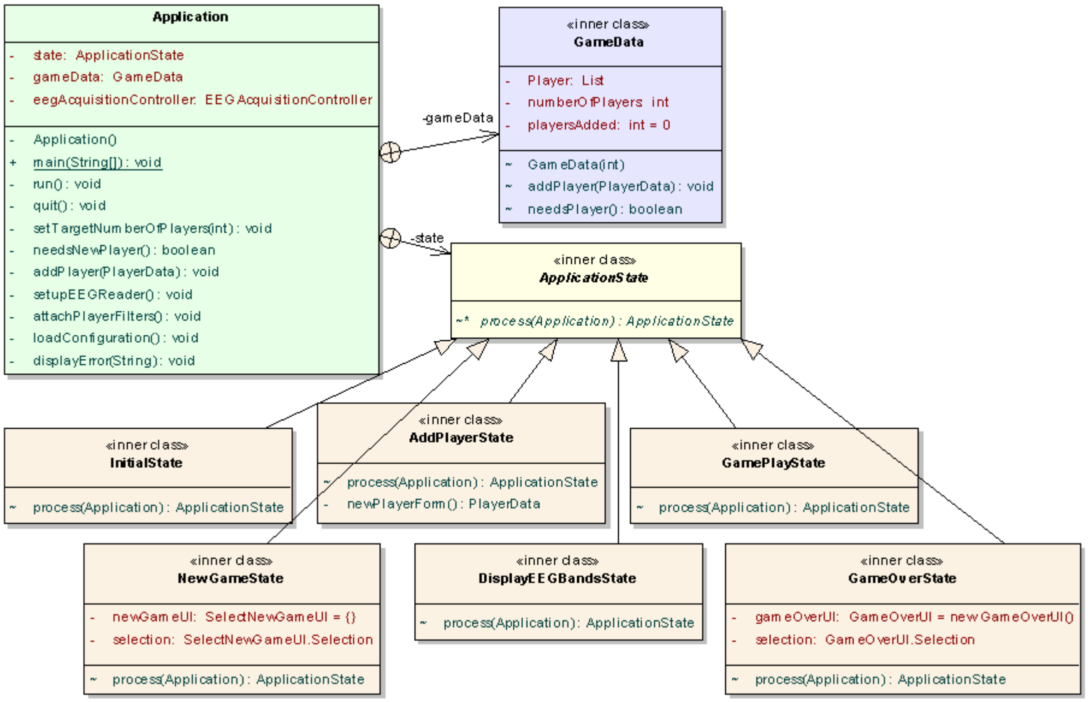


Figure 3.31: The `Application` class uses internal `ApplicationState`s to control its logic

bands of beta, alpha, theta, and delta. A test class was created for each component using JUnit and a test suite that ran all tests [21].

After the data pipeline was built, the first of the three courses was created. During the development of the second course, common course code was isolated and extracted to an abstract course superclass. Implementation of the third course took only a few hours, as the common course logic was already written.

Chapter 4

Evaluation

To evaluate our application, we configured the game to target alpha brainwave frequency ranges and had a group of volunteers play multiple times. We recorded each player's brainwave activity during gameplay and analyzed this data to determine if the game was effective at encouraging activity in the target frequency ranges. We expected that activity in the target ranges would change during the course of the game, as the player was encouraged by the game feedback. We also expected that repeat play would result in better control of one's brainwave activity.

4.1 Method

4.1.1 Participants

Sixteen people participated in the study: 5 men and 11 women. Participation was voluntary and based on the players' availability. Six of the participants were able to play four sessions over four weeks of testing. One person participated in three sessions, four people played two sessions, and five people participated in a single session.

4.1.2 Neurofeedback Training Protocol

The three courses in Brainathlon were each configured to encourage activity in the alpha frequency range (8-12Hz). Alpha training is common in peak performance protocols and is used to reduce stress, increase creativity, and improve ability to perform under pressure [43].

Beta waves (12-20Hz) are commonly associated with thinking, having an external focus, and being immersed in the outside world. Theta waves (4-8Hz) are associated with an internal focus and the subconscious. The alpha frequency band lies between beta and theta, and some neurofeedback researchers describe alpha waves as the bridge between the external world of beta brainwaves and the internal world of theta waves [58][61]. A lack of alpha activity is therefore associated with a disconnect between the conscious and unconscious mind, and an avoidance of self awareness. These researchers suggest that alpha training can provide subjects with balance and access to an inner calm. With a bridge between external and internal focus, the subjects can more easily shift to an appropriate focus. This capacity to shift in order to better handle obstacles is common in peak performers and is a primary focus of peak performance training [43].

Course #1, the Band Increase Course, was configured to reward high amplitude alpha activity. The Sustained Increase Course, course #2, was configured to reward moderately high sustained alpha activity. The goal time for course #2 was set for five seconds, so the players were required to sustain moderately high alpha activity for five consecutive seconds.

The Dual Band Ratio Course, course #3, was configured to encourage high-frequency alpha in the 10-13Hz range over low-frequency alpha in the 7-10Hz range. During gameplay, as the player produced more high-frequency alpha than low-frequency alpha, the ball moved toward the finish line. When they produced more low-frequency than high-frequency alpha, the ball moved away from the finish line.

This high-alpha to low-alpha ratio was chosen based on studies linking high-frequency alpha production to increased memory performance [34][3]. Also, in Joe Kamiya's early neurofeedback experiments, subjects were able to gain conscious control over their ability to produce both higher-frequency alpha and lower-frequency alpha within a short training period [32].

4.1.3 Testing Sessions

A testing session consisted of playing the entire three-course game three times in a row. Each of the courses in the game was configured to have a five-minute limit. Each course ended when the player either won the course or reached the end of the time limit. Therefore, the entire three rounds in a testing session contained a 45 minute maximum of neurofeedback training but was quicker if the player won any of the courses.

The sessions took place in a quiet home office with the players seated at a desk in front of a laptop computer. The test administrator was seated on a couch next to the desk and was available to answer any questions. Test subjects were instructed to remain still during the testing in order to reduce artifacts caused by movement. They were also instructed to keep their eyes open, as closing the eyes typically increases alpha activity.

The subjects chose to play alone or play competitively, and some subjects switched between one and two-player gameplay from session to session.

4.1.4 EEG Recordings

Electrode placement was determined according to the "10-20 International System of Electrode Placement." This system is based on the location of the cerebral cortical regions [13]. Since people have differently sized heads, the system uses percentages to determine placement. Electrodes are spaced at 10% or 20% of the total distance between fixed skull locations such as the nasion (bridge of the nose) and inion (base of the skull). Figure 4.1 illustrates the 10-20 system of electrode placement.

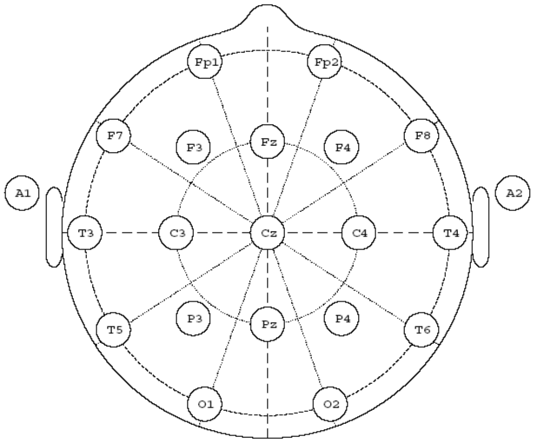


Figure 4.1: Electrode placements in the 10-20 system

EEG data was collected at the scalp site Cz, referenced to the left ear A1. A third electrode, called the "right leg driver" was attached to the left arm to cancel 60Hz mains hum.

The active electrode site used, Cz, is the center location along the midline of the head, between the nasion and inion. It is a commonly used placement for single electrode neurofeedback [58][36][9]. This central location avoids many of the muscle movement artifacts that are common in other locations. Frontal locations are likely to pick up noise from eye movements, and posterior locations may pick up muscle movement artifacts from the muscles in the neck and shoulders. The midline location allows us to detect activity in both brain hemispheres.

Brainathlon uses only one active electrode per player. Research shows that using a single electrode is common and successful in producing widespread changes [43][36]. Using multiple channels and averaging them is not recommended, as the sum of activity at multiple sites gives no indication of the actual activity at each individual site [36].

4.1.5 Data Analysis

Each player's average alpha (8-12Hz) amplitude was recorded once per second during courses #1 and #2. This data was used to calculate an average amplitude value per course. The per-course averages were compared for each of the three rounds played in a session to determine if alpha activity increased with repeated game play.

During course #3, the players' average high-frequency alpha (7-10Hz) and low-frequency alpha (10-13Hz) amplitudes were recorded once per second, and these values were used to calculate the average ratio per second. An overall average ratio value was calculated for the course, and per-course averages were compared for each of the three rounds played in the session to determine if the ratio increased with repeated game play.

4.2 Results

4.2.1 Course #1 - Band Increase Course

We analyzed 15 players' average alpha amplitude during the Band Increase Course portion of the three repeated rounds played during the first session. (One player was excluded from the analysis because she accidentally played the first course with closed eyes, which increased alpha production.) The mean value for each round is shown in Table 4.1. We used a repeated measures analysis of variance (ANOVA) to test the difference in mean alpha amplitude across round 1 to round 3. The means are reliably different from one another, F(2, 28) = 10.20, $p < .001$, indicating that repeated game play results in increased alpha activity.

Trial	**Mean Alpha Amplitude**
Round 1	5.68
Round 2	6.03
Round 3	6.38

Table 4.1: Band Increase Course results for 1 session

We then averaged the Band Increase Course averages from all three rounds to calculate an overall average for each session. The average alpha amplitude during each session was analyzed for the six players who completed four sessions. Although six players were not sufficient for statistical significance, this data indicates that alpha activity continues to increase with repeated game playing sessions spread out over several weeks. Table 4.2 contains the combined mean alpha amplitudes for the three rounds in each of the four separate sessions.

Trial	**Mean Alpha Amplitude**
Session 1	6.54
Session 2	6.71
Session 3	6.95
Session 4	7.58

Table 4.2: Band Increase Course results over 4 sessions

One-Player vs. Two-Player Game Mode

The data from one-player and two-player games was also analyzed separately to determine if either mode was more effective in increasing alpha activity. Although the player's average alpha amplitude was higher for those who played alone, both modes resulted in increased alpha activity with repeated game play. A repeated measures ANOVA showed that both modes produce significant improvement (one-player mode: F(2, 14) = 6.35, $p < .01$, two-player mode: F(2, 12) = 4.65, $p < .03$). Table 4.3 shows the results for the eight participants who played in one-player mode, and Table 4.4 show the results for the seven who played in two-player mode.

One-Player Game Results

Trial	**Mean Alpha Amplitude**
Round 1	6.14
Round 2	6.43
Round 3	6.99

Table 4.3: Eight players, 1 session

Two-Player Game Results

Trial	**Mean Alpha Amplitude**
Round 1	5.15
Round 2	5.57
Round 3	5.70

Table 4.4: Seven players, 1 session

4.2.2 Course #2 - Sustained Increase Course

We analyzed the first session's average alpha amplitude values during the Sustained Increase Course for all 16 players. The mean value for each round is shown in Table 4.5. We again used a repeated measures ANOVA to test the difference in mean alpha amplitude across round 1 to round 3. For this course, the means are also reliably different from one another, F(2, 30) = 7.81, $p < .002$. This shows that repeated game play results in increased alpha activity for this course as well.

Trial	**Mean Alpha Amplitude**
Round 1	6.34
Round 2	6.78
Round 3	7.17

Table 4.5: Sustained Increase Course results for 1 session

As with course #1, we averaged the Sustained Increase Course average amplitude from all three rounds to calculate an overall average for each session, and we analyzed this for the six players who completed four sessions. The resulting values fluctuate but suggest a generally increasing trend. Mean alpha amplitudes for the three rounds in each of the four separate sessions are shown in Table 4.6.

Trial	**Mean Alpha Amplitude**
Session 1	8.00
Session 2	7.89
Session 3	8.86
Session 4	8.54

Table 4.6: Sustained Increase Course results over 4 sessions

One-Player vs. Two-Player Game Mode

One-player and two-player game data was separated and analyzed to determine if either mode was more effective at encouraging increased alpha activity. As with course #1, the player's average alpha amplitude was higher for those who played alone, but both modes resulted in increased alpha activity with repeated game play. A repeated measures ANOVA showed that people playing the one-player game demonstrated improvement approaching significance, F(2, 14) = 3.51, $p < .06$, and people playing the two-player game showed significant improvement, F(2, 14) = 4.65, $p < .03$. Tables 4.7 and 4.8 show the results for the one and two-player mode participants.

One-Player Game Results

Trial	**Mean Alpha Amplitude**
Round 1	7.32
Round 2	7.82
Round 3	8.29

Table 4.7: Eight players, 1 session

Two-Player Game Results

Trial	**Mean Alpha Amplitude**
Round 1	5.37
Round 2	5.74
Round 3	6.04

Table 4.8: Eight players, 1 session

4.2.3 Course #3 - Dual Band Ratio Course

The average ratio of high-frequency alpha to low-frequency alpha was analyzed for the Dual Band Ratio Course portion of the three rounds played during the first session, using data from all 16 players. Mean ratio values for each round are contained in Table 4.9. A repeated measures ANOVA showed no effect on average ratio across repeated rounds, F(2, 30) = .99, $p < .38$. This indicates that players do not readily improve their ability to consciously control high to low alpha ratio in three rounds of game play.

Trial	**Mean Ratio**
Round 1	.95
Round 2	.88
Round 3	.92

Table 4.9: Dual Band Ratio Course results for 1 session

We also averaged the Dual Band Ratio Course average ratios from all three rounds to calculate an overall average for each session, and we analyzed this for the six players who completed four sessions. The results suggest that repeated gameplay may improve players' ability to increase their ratio of high-frequency to low-frequency alpha after 4 or more sessions. The mean ratio values for each of the separate sessions are shown in Table 4.10.

Trial	Mean Ratio
Session 1	.92
Session 2	.94
Session 3	.92
Session 4	1.12

Table 4.10: Dual Band Ratio Course results over 4 sessions

One-Player vs. Two-Player Game Mode

The data from one-player and two-player games was analyzed separately for this course as well. Although the two-player mode participants showed a slight improvement over their three rounds of gameplay, neither mode was successful at encouraging significant improvement in one session. Table 4.11 shows the results for the eight participants who played in one-player mode, and Table 4.12 show the results for the eight two-player mode participants.

One-Player Game Results

Trial	Mean Ratio
Round 1	1.04
Round 2	.89
Round 3	.92

Table 4.11: Eight players, 1 session

Two-Player Game Results

Trial	Mean Ratio
Round 1	.86
Round 2	.87
Round 3	.93

Table 4.12: Eight players, 1 session

4.3 Discussion and Future Work

4.3.1 Neurofeedback Training

The results show that players can learn to consciously increase their alpha activity by playing the first two courses in Brainathlon. Each course lasted a maximum of five minutes, and on average players improved in course #1 and #2 from one round to the next. This demonstrates that improvement in conscious control of alpha activity can be achieved with only a few minutes of training. Repeated gameplay spread out over several weeks results in continued improvement.

These findings are consistent with early neurofeedback experiments, such as those performed by Joe Kamiya in the early 1960s [32]. Control over brainwave activity in the alpha frequency band can be learned through neurofeedback training.

A player's ability to control the ratio of high-frequency to low-frequency alpha did not show the same improvement, although there was some suggestion that repeated practice may eventually lead to improved control. This suggests that controlling the ratio of one frequency band to another is more difficult to learn than simply increasing the activity in one band.

Beta to theta ratio training is common in clinical neurofeedback therapy for attention deficit disorder (ADD) and attention deficit hyperactivity disorder (ADHD), which indicates that the ability to consciously control the ratio of two frequency bands can be learned. However, ADD/ADHD treatments typically include 35-50 training sessions [36]. A longer study would be needed to determine if Brainathlon's course #3 could train players to control their ratio of high-frequency to low-frequency alpha.

A possible explanation for the performance differences may be that courses #1 and #2 rewarded very similar activity, while course #3 rewarded a different type of brain activity. A session contained six course trials encouraging an increase in alpha amplitude but only three trials encouraging an increase in the ratio of high-frequency to low-frequency alpha.

4.3.2 Directions for Future Work

In general, players reported that they enjoyed the game and found it interesting. Participants who played the two-player game tended to report more enjoyment if they won many of the courses and less enjoyment if they lost many or all of the courses. Players seemed to find the game frustrating if they did not do well. Conversely, several players suggested making the game more difficult once they learned to quickly win. A future study that adjusted amplitude and scoring variables to make the game challenging yet winnable for each of the subjects could prove interesting. The amount of improvement from one round to the next may be affected by the players' success with the game. Another potential future study would further compare the players' improvement in brainwave control between the one-player and two-player versions of the game.

The players were all volunteers who received no compensation for their participation. Some people were available for weekly sessions at the same day and time, while others varied their day and time based on their availability. Availability also affected whether subjects played alone or against an opponent. These variances could affect the quality and validity of the data collected.

When the game was played by two competing players, the amount of time spent in each course was often determined by the winning player; the course would come to an end when the winning player won. Therefore, when analyzing the data from two-player games, it is difficult to compare the data of the losing player to that of players who played alone and may have had more time to play and win the course.

Ideally, day, time, and game type would have been controlled in our study, and we would have had a pool of available test subjects large enough to compare one-player game improvements with two-player game improvements. Additional studies are needed to fully analyze the effectiveness of Brainathlon as a neurofeedback tool.

4.3.3 Summary of Findings

This initial study showed that Brainathlon can be used to gain conscious control over one's ability to increase alpha brainwave activity. Although the findings for the Dual Band Ratio course were inconclusive, further studies may find that players gain conscious control over their ratio of high-frequency to low-frequency alpha if they participate in additional game playing sessions.

Chapter 5

Conclusion

EEG-based brainwave monitoring devices have been used to create many profoundly useful applications. Assistive technology researchers, for example, have created systems that enable hands-free control of computers for severely disabled patients who previously had no means of communicating with the outside world. In addition, neurofeedback provides a promising treatment option for a wide range of conditions. Conditions such as ADD/ADHD and epilepsy are commonly treated with drug therapy, but the drugs used are known to have negative side effects and are an ineffective treatment for many patients. Neurofeedback offers an alternative treatment for those who can't benefit from drug therapies or who are looking for a drug-free solution.

These applications of EEG-monitoring inspired the present work to design and develop an EEG-based application. The goal of this project was to create a free, configurable neurofeedback application for use by non-technical people, and to develop a set of reusable libraries to support the development of future applications.

5.1 OpenEEG

Although open source is typically associated with software development, the open source model provides an opportunity for the collaborative development of systems that combine both hardware and software. In an open source project, developers with expertise in different areas can work together and build upon the contributions of others. The systems developed provide building blocks for future contributions, and the value of the contributions continue to grow.

The OpenEEG project provides a low cost method for brain-computer interface application development. The project consists of both free software and schematics for building an EEG device. The project's ModularEEG device can be built for under $500, and it can be built by someone with limited electronics experience. With free software and inexpensive hardware, the project allows affordable access to neurofeedback. The project also presents an opportunity for the development of low cost systems for assistive technology.

5.2 Brainathlon

This thesis presents the open source Brainathlon software game and libraries that were designed and developed as a contribution to the OpenEEG project. Brainathlon provides a free neurofeedback game that can be used with the ModularEEG device. The game offers an entertaining format for neurofeedback training and improved self-awareness. When played alone, the game can be used for traditional neurofeedback training; when played with an opponent, the game presents an interesting opportunity for two people to share a glimpse of each other's inner world of brainwave activity.

The Brainathlon game was built upon the developed set of reusable libraries for EEG acquisition and analysis. The acquisition library interfaces with the existing OpenEEG NeuroServer program to read raw samples from the ModularEEG device. The analysis library includes components for designing digital filters to isolate specific bands of brainwave activity. The library also includes components that calculate average brainwave amplitude values. The architecture of the libraries provides a pluggable framework for creating an EEG acquisition and analysis pipeline.

5.3 Summary of Contribution

This thesis contributes both a software application and software building blocks to support the development of future applications. The software has been contributed as open source to the OpenEEG project. In addition, it has been demonstrated that the Brainathlon game is an effective tool for enhancing alpha brainwave activity. In summary, the work contributes:

- A set of open source, reusable Java libraries to support the creation of future brain-interface applications for the ModularEEG device. These libraries provide a toolset for EEG acquisition and analysis, and they supply a framework for the addition of new analysis components created in future development.
- A configurable open source game for one or two players that encourages brainwave activity in user-specified frequency ranges. The game can be easily customized and used by non-programmers.
- A game configuration that enhances alpha brainwave activity. The evaluation showed a strong correlation between repeated game play and increased average alpha amplitudes.

The Brainathlon project provides a number of opportunities for future use. The game can be used as it is currently configured, or it can be customized to encourage brainwave activity in different ranges. A programmer could easily add new course modules using the current application framework and abstract course superclass. The libraries could be used to create a different type of application for the ModularEEG device, or the libraries could be extended to provide additional EEG analysis components.

EEG-based applications show great promise for use in assistive technology, neurofeedback, self-awareness and entertainment. The Brainathlon game offers an effective tool for neurofeedback training and an interesting form of entertainment. The Brainathlon libraries provide a foundation for building applications with the low cost ModularEEG device. The author hopes that the Brainathlon software proves useful in the development of future brain-computer interface applications.

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