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Adaptive Audio Engine for EEG-Based Horror Game

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ABSTRACT

This paper documents the design and play-testing of a videogame that incorporates electroencephalography (EEG) technology to augment traditional controls. A survival horror game was created using Unity3D. The player navigates the game using conventional keyboard and mouse movement, however, they also wear an Emotiv EPOC headset which transmits their level of calm to the game via OSC. In order to complete the game, the player must remain as calm as possible. An adaptive audio engine was developed to act as an auditory display for this complex parameter, in lieu of a distracting visual indicator. Every element of the audio was designed to adapt to the constantly fluctuating value. Procedural audio modules were created in Max, where player EEG data was simultaneously mapped to a myriad of modulators. FMOD Studio was used for non-procedural elements due to its facilitation of real-time control parameters, as well as its integration with Unity3D.

1 INTRODUCTION

The gaming industry is relentlessly burgeoning. A significant advantage it holds over competing entertainment mediums is its boundless agility. While the format of, for example, a movie, remains relatively static, videogames can utilize the newest technology in their next product cycle. Resultantly, the medium is constantly changing. The adoption of emerging technologies prompts new ways for the player to experience the art form. A core facet of this agility lies in the incorporation of external technologies; tools which allow the player to interact in new and unique ways.

Indeed, we are poised on the advent of a potentially revolutionary period for videogame production. Developments over the next five-to-ten years, such as the *Oculus Rift,* may completely reshape the landscape of the industry, as gaming and virtual reality coalesce to form a hybrid experience, as innovative as it is exciting. Another such external technology with potential for gaming integration has been utilized in the project presented here: electroencephalography.

Abbreviated to EEG, the method facilitates the recording of brain activity by using multiple electrodes positioned on the user's scalp. Voltage fluctuations can convey various cognitive states, such as engagement, meditation, excitement, and more. With the introduction of low-cost Brain-Computer Interface (BCI) devices to the consumer market, research using such instruments is now readily accessible, accelerating the adoption of the technology. As will be shown in the forthcoming, the incorporation of EEG within games may lead to new paradigms of player control, as well as new levels of immersion.

This paper not only documents the creation of *Slasher,* an EEG-based horror game; it also attempts to demonstrate the need for such a project by assessing the state of the art in the technologies used to create the game. The remainder of this introduction will substantiate the importance of immersion in videogames, before offering an overview of the project. Sections two and three review background work in the fields of game audio and EEG respectively. Section four illustrates the methodology used in making the game before chapter five quantifies and analyzes the results. A discussion section critiques the impact of the work before a final conclusion is offered.

1.1 The Quest For Immersion

We gasp; we claw; we sigh; we scream: as we reach that pinnacle state of immersion while playing a videogame we are effervescent in posture, erratic in disposition. We become emotionally present as we ultimately succumb to the fiction. As a result, our levels of both engagement and enjoyment increase [1]. But this utter encapsulation can only transpire if the unfolding events feel indubitably realistic; we must be thoroughly convinced. Should anything burst that bubble of augmented reality, our experience is significantly dented, sometimes irrevocably. Consequently, it is the goal of any game developer to sculpt a highly interactive and immersive environment, tricking the player - by any means necessary – into the belief that what they see and hear is real.

Audio plays a crucial role in upholding the credibility of the ruse. At the very least, the sound of a game must keep pace with its visual counterpart. If the game aesthetic is hyper-realistic, the audio must be faithful to the real world, propagating from point sources in three-dimensional environments. If the game is set in fantastical or futuristic worlds, then the player still has an expectation as to how these settings *should* sound, despite them having no basis in reality. But the task of sculpting a realistic aural experience goes further than just having exceptional sound design; the entire audio *implementation* must be executed in accordance with the game's context.

Successful EEG integration has obvious benefits towards creating an immersive gaming experience, connecting the player to the game in ways that far exceed the linear nature of traditional controllers. But going further still, it offers new avenues of audio implementation. If the audio of a game can keep pace with both the visual element of the environment as well as the fluctuating mindset of the player, the result will undoubtedly stand as a highly immersive product.

1.2 Project Overview

An EEG-based horror game called *Slasher* was created, in which the player's real-world emotional state directly affects the character they control in the fictional world. Set in an abandoned asylum, the player must remain calm in order to escape the building, overcoming various tasks along the way. The more anxious or frightened the player becomes, the harder the tasks are to complete, thus the more likely the chance of death. Incorporation of EEG technology here can be seen as an augmentation of conventional controls: the player must perfect their psychological state as well as the physical controller.

At all times, the player is informed of their *level of calm* via sound only. There are no visual indicators. This auditory display is comprised of procedural audio modules and other adaptive events. The soundscape becomes manifestation on the player's emotion.

Motivation for the project draws from the recent success of virtual reality products, combined with the perpetual quest for player immersion in video games. A dissection of the term 'immersion' in this context could be stated as "placing the player inside the game." With VR devices, the player appears visually inside the virtual world. With EEG technology, the player can now feel emotionally connected to that landscape.

2 AUDIO FOR VIDEOGAMES

The field of audio for videogames continues to grow in complexity. The role of audio in games has evolved from simple background music [2] into a vital tool for the designer in communicating information to the player. In *Slasher*, the audio attempts to relay a complex and unorthodox parameter – the player's *level of calm* - freeing space on the screen from unnecessary UI components.

The remainder of this chapter investigates how both adaptive and procedural audio can be effective in communicating information to the player in real-time.

2.1 Adaptive Audio

The need for adaptive music due to the non-linear nature of games has been well documented [3][4][5]. When incorporated effectively, adaptive music can alleviate repetition by ensuring similar passages are not looped endlessly, and can communicate information to the player by using specific instrumentation to symbolize game events. Horizontal re-sequencing and vertical re-orchestration are common techniques in modern game music soundtracks. The former uses pre-composed segments of music which can be played-back in any order, depending on game events. The latter dynamically adjusts the mix in reaction to game-state data, for example: drums and percussion fade up in the mix during a combat scene. Rockstar Games' 2010 title *Red Dead Redemption* makes extensive use of both techniques, requiring over 14 hours of original music to cover the plethora of routes the narrative may take [6]. An 'Adaptive Music Event' used in *Slasher* makes use of vertical re-orchestration to communicate the *level of calm* to the player.

2.2 Procedural Audio

Procedural audio is inexorably linked with *physical modeling*, a full discussion of which lies out-with the scope of this paper, however the intrigued reader is referred to [7]. To summarize briefly, the technique involves modeling the vibrational patterns of objects while they are performing sound energy. Models tend to be very complex and require robust CPUs to perform the necessary synthesis. A less intensive technique is required.

Andy Farnell presents a myriad of practical implementations of procedural audio in his esteemed book Designing Sound [8]. Each practical example begins with a systematic dissection of the objective sound, identifying every mechanical element that contributes to the overall sonic production. For example, a gunshot (page 594) comprises detonation, excitation, expulsion, recoil, and bullet sounds. Each of these elements provokes certain vibrations in the physical parts of the gun – piston, recoil spring, eject port, barrel, *etc*. – which collectively contribute to the overall modal vibration. By carefully analyzing the *procedures* involved in the sound's production, it can be *modeled*. Certain procedural sound modules within *Slasher* were directly influenced by Farnell's exemplary work.

Although based on principles of physical modeling, Farnell's technique should be regarded as a type of *abstract synthesis* [12]. Farnell posits that his implementations are ideal for real-time interactive environments, such as videogames, due to their reduction in computational demand in comparison to full modal synthesis. Indeed, we are beginning to observe tentative steps into such application. The work presented in [31] exhibits simple pen stroke sounds, which are modeled for use with tactile devices. An audio recording of a real-world pen stroke sound is used in the estimation of an excitation signal, which is then input to the model.

Environmental ambiences, such as wind and rain, are relatively easy to simulate using enveloped and filtered noise. These ambiences often permeate entire games and can be rather tedious to implement using sample-based methods. A solution is provided by plug-in developers AudioGaming [9], who have designed a procedural audio weather system for use in FMOD Studio. Individual volumes for wind and rain can be mapped to any in-game parameter, meaning they can be continuously modulated. A simple example would be mapping the volume of rain to the player character's distance from an open window.

Mapping procedural parameters to external control highlights one of the key advantages to procedural audio; not only can variety be achieved by using a continuously changing control signal, but also new levels of realism can be reached by utilizing physical measurements calculated from the virtual environment. Niels Bøttcher attempts exactly this in his use of a Nintendo Wii remote to drive a synthesized weapon sound in a first-person sword game [10]. The project determines whether the realism achieved by this implementation improves the player's 'motorical' ability; does realistic sound help the player become better at the game?

2.2.1 Physics-Driven Procedural Audio

It is intuitive to use physics data in the mapping of procedural parameters; the harder the player strikes a weapon against an object, the louder its impact sound should be. Physics-driven animations are used to control granular synthesis in [11]. To implement the technique, audio files were pre-processed, being manually *sliced* into separate grains. In the virtual environment, certain collisions and movements are mapped to these grains, which are triggered in an order dependent on the respective force or velocity of the action.

In [12] a framework is exhibited in which users can craft graphical objects for an interactive environment. Physical parameters are derived from the type of material chosen – as well as the object's dimensions – and linked directly to a sound synthesis engine. In a similar project, Dylan Menzies presents his *Phya* software [13], described as "a library that facilitates physical modeling for sound synthesis in tandem with a physics engine." The program allows the user to first create a graphical object, and then assign different sounds for various types of contact, including: simple impacts, multiple impacts, grazing sounds, slipping and sticking due to friction, buzzing due to vibration, plus many more.

2.2.2 Emotion-Driven Procedural Audio?

With mechanisms in place for procedural models to *react* to some input data, such as physics information, one must consider the option of using the player's real world emotion to drive the virtual world's soundscape. Indeed, that is precisely what *Slasher* attempts to do: the player's real world calmness affects background ambiences emanating from the virtual environment, as well as foreground sounds emitting directly from their character. Before continuing any such discussion, we must now turn to a technology which allows us to harness such personal data: Electroencephalography.

3 ELECTROENCEPHALOGRAPHY

The discovery of Electroencephalography is credited to the German neurologist Hans Berger, who coined the term in 1920s after recording electrical signals from the human brain [14]. The term, derived from the German phrase "brain electricity writing", was first documented by Berger in 1929 [15] although his pioneering paper was not translated into English until 1969 by Pierre Gloor [16]. 'EEG' is the accepted abbreviation and will be used in the forthcoming.

3.1 The Human Brain

Electrical activity inside the human brain is the result of transmission through pyramidal neurons within the cerebral cortex [17]. The neurons themselves do not move, rather an *action potential* moves through an entire neuron cell, before jumping to the next neuron. A jump is required because adjacent neurons are separated by an area called the synaptic cleft.

A negative charge is emitted as neurotransmitters move across the synaptic cleft, an occurrence which is crucial to EEG detection. The area around this neuron becomes temporarily negatively charged. An electric dipole is thus created between this area and another distant area of the neuron, which is positively charged. When this process occurs in many parallel cells, their individual dipoles summate to create one large dipole, which can be detected from outside the skull using electrodes.

3.2 EEG Devices

Electrodes are placed in specific locations on the scalp, most commonly using the internationally-recognized '10-20' system (Figure 1) which facilitates consistency across EEG recordings. Each electrode detects transmission when action potentials occur in its relative area. The collective frequency of these messages is significant, as will be shown. The signal from each electrode is generally very small, so it must be amplified. This inherently raises the noise floor, therefore specific filtering must occur: high-pass and low-pass filters combine to attenuate below ~1hz and above ~30Hz [18] leaving a target bandwidth that we will now investigate.

Our target band can be divided into four clinically significant sub-bands: Delta (<4 Hz), Theta (~4-8 Hz), Alpha (~8-13Hz), Beta (13-30Hz). Delta waves normally occur in deep sleep and young babies. Theta waves do not typically appear in awake adults and are associated with sleep, although they are sometimes present in awake children. Alpha waves are generally present in adults who are in a relaxed state with closed, or partially closed, eyes. Beta waves are more commonly detected in alert or excited adults. This is summarized in Table I.

Table I - Summary of EEG Frequency Bands

Band	Frequency	Observed
Delta	<4 Hz	Deep sleep, babies
Theta	4-8 Hz	Adult sleep, awake children
Alpha	8-13Hz	Relaxed adults
Beta	13-30 Hz	Alert adults

The Emotive EPOC EEG headset was used in this project, worn by test subjects as they completed *Slasher*. The headset contains 14 electrodes, which are positioned in accordance with the '10-20' system. The data is recorded at a sample rate of 128 Hz. The subsequent signal is high-pass filtered at 0.16 Hz and low-pass filtered at 85 Hz [19]. The EPOC ships with software that allows the user to view certain EEG data. This project utilized just one stream of EEG data: *calmness*.

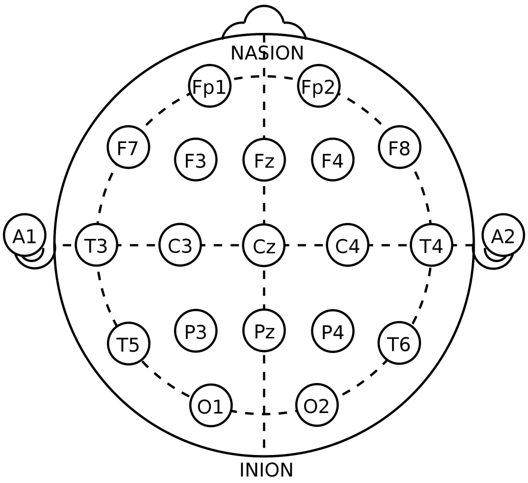

Figure 1 - The '10-20' Electrode Positioning System [20]

3.3 EEG for Music Composition and Performance

EEG devices have been used in musical composition for over fifty years. It is a relatively common implementation that is attractive due to the notion of creating *brain-controlled music*. In 1965 Alvin Lucier performed his piece *Music for Solo Performer,* in which he linked his own EEG data to various percussive instruments [21]. The piece is believed to be the first documented attempt to use EEG data as an input for musical composition. Lucier sat calmly on a stage, with electrodes fitted to his scalp. The signal was amplified and filtered so that only alpha waves were present. Being so low in frequency, the alpha waves were able to drive vibrations in different instruments arranged around the performance space, due to careful placement of loudspeakers [22].

In the 1970s David Rosenbaum began systematic research exploring the potential for EEG in the generation of artistic works. By 1990 he introduced a technique which mapped EEG data to a generative music system; performers controlled the composition by selectively shifting their attention [23]. Rosenbaum's work was built-upon in 2003 by Miranda, et al., who placed more emphasis on *how* EEG data was mapped to musical parameters; they found ways to "harness the EEG signals and extract meaningful musical information from them," [24].

More recently, a work titled *Music for Sleeping & Waking Minds* mapped EEG data from four sleeping performers to a compositional system during an 8-hour musical performance [25]. Performers wore EEG headbands made by Infusion Systems, data from which was processed in Max and used to drive an 8-channel soundscape.

3.4 EEG in Gaming Technology

In *Slasher*, player EEG data is mapped to an adaptive audio engine, as has been discussed. However, it is also mapped directly to elements of the gameplay. The player must be able to control their *level of calm* in order to successfully complete the game. In this sense, the EEG device augments traditional game controls: the player must be just as tactful with their mind as they are with their hands.

Low-cost EEG devices are targeted at the gaming market, presumably with the goal of one day becoming a regular extension to conventional controllers. Some work has been done that tries to incorporate EEG into elements of the gameplay. In 2009, Ko, et al., published an investigation into the potential of BCI-based gameplay [26]. To test some of their hypotheses about how the technology could be applied to gameplay, they designed a collection of short prototype games, for which players wore NeuroSky's *Mind Set* EEG headset. Player EEG data augmented keyboard and mouse input in various ways. Test results indicate that subjects benefited from the use of EEG as a controller, as it provided them a "more intuitive and interesting experience" [26].

In [27] the Emotiv EPOC headset is used as a game controller *in place of* conventional control interfaces. The project does not present a game, rather it demonstrates EEG-controlled navigation of a simple user interface. To facilitate the implementation, the authors worked with raw EEG data, first filtering it in Matlab, before programming it into their custom-designed interface using C#. Initially intended to facilitate gaming control for handicapped persons, the work was extended to target all user types, with a view to replacing "old-fashioned" interfaces such as the keyboard and mouse. In *Slasher*, the EPOC headset in used *in tandem* with conventional controllers, to arguably greater success. A comprehensive review of games involving EEG and other BCI devices can be found in [28].

4 TECHINICAL IMPLEMENTATION

The forthcoming section documents the technical implementation of *Slasher,* with a focus on the adaptive audio engine. The game was created by the author, using the Unity game engine [29] combined with various software. For a comprehensive review of all project elements, as well as video examples of the game, the reader is referred to the author's portfolio website[1].

4.1 *Slasher*

The somewhat whimsical premise of *Slasher* is as follows. It is set in the post-biological age, where the human body contains computerized parts that help regulate performance and health. Metallic arteries are used to regulate blood temperature, however, they emit a small electromagnetic field in doing so. Zombie-like enemies can sense the presence of the player by detecting this electromagnetic field. The more agitated the player becomes, the faster the blood runs, thus the stronger the electromagnetic field and the easier they are to detect. The enemies in the game are essentially blind to everything except this form of detection.

The game has three distinct levels. In level one the player must progress through locked doors by finding the keys that unlock them. Each key is placed within the vicinity of an enemy, at a very specific distance. The player must be calm enough that they can approach the key and pick it up without enemy detection. During their approach, the player must monitor the soundscape produced by the adaptive audio engine and discern whether or not they are calm enough to collect the key without enemy detection.

In level two, the player must navigate a dark basement using a night-vision app on their smartphone, which doubles the enemies' detection sensitivity when turned on. The main threat in the basement is an enemy that stalks the player from the offset. The player's *level of calm* has an affect on their movement: when calm, the player moves quickly and smoothly; when agitated, the player moves very slowly and erratically.

In level three, the player is equipped with a gun and must shoot their way past an onslaught of spawning enemies. The spawn rate is linked to the player's *level of calm*. When the player is calm, new enemies spawn at a lower rate, around every 6 seconds. When the player is less calm, new enemies spawn at a higher rate, around once-per-second. In this section, an adaptive music event is used to convey the player's *level of calm.*

4.1.1 Communication and Signal Flow

Figure 2 presents a useful graphic illustrating the communication and signal flow between the various software and hardware used to implement and play the game. Unity can be thought of as the center of the diagram; this is where the game takes place, therefore it is the location most of the data is trying to get to. Sound output comes from several simultaneous sources. User input comes from two discrete areas: mouse and keyboard facilitate traditional control; the Emotive EPOC EEG headset facilitates psychological control.

With the EPOC, there is no *plug-and-play* option for transmitting the EEG data to Unity or Max. Instead, the data is sent from the Emotiv Control Panel via OSC - using a 3rd party application called MindYourOSC (available on the Emotive eStore for free download) – to Max, where it is used to modulate parameters in procedural audio patches. Max handles OSC data very well, thus it is used to pass the EEG data along to Unity, using C# scripts posted on GitHub by Jorge Garcia [30].

FMOD functions as a *plugin* to Unity, facilitating a communication protocol between the two applications. This allows game data from within Unity to modulate parameters in FMOD in real-time. Specifically, the game sends player EEG data values to FMOD which adjust a real time parameter controller (RTPC) on various sound events. Resultantly, player emotion is used to control adaptive FMOD events.

Overall, this is a highly interactive and reactive system, in which multiple programs work together to transmit and control player EEG data. As stated, the only EEG

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[1] http://jordancraigportfolio.com/#/slasher/

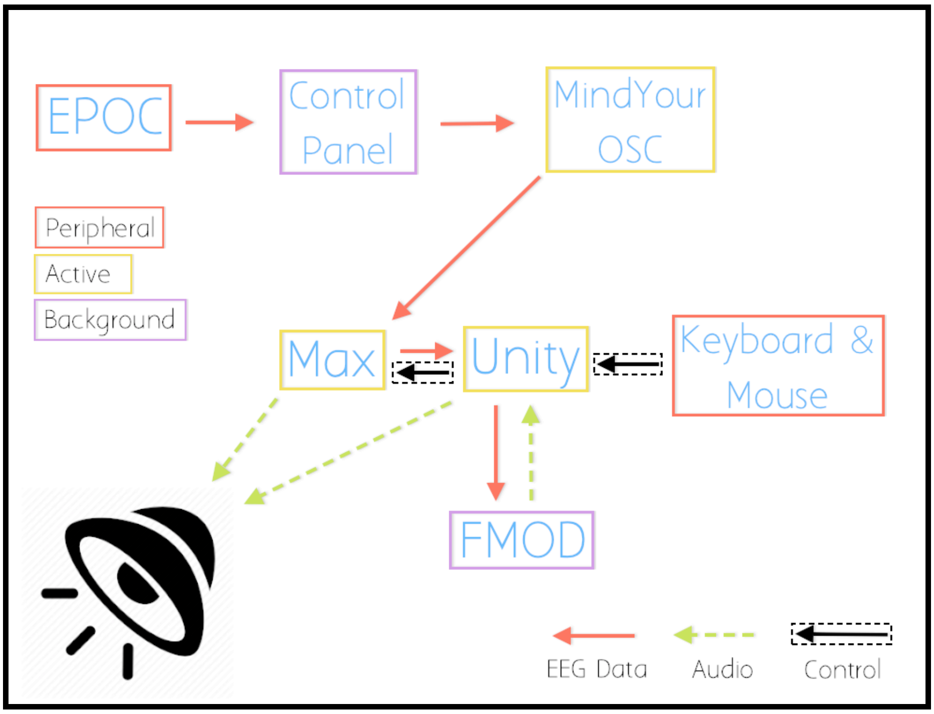

Figure 2 - Communication and Signal Flowchart

data used is player *calmness,* normalized between 0 and 1; 0 means very calm, 1 means very agitated.

4.2 The Adaptive Audio Engine

The core goal of this project was to develop an adaptive audio engine that could act as an auditory display for the player, informing them at all times of their psychological state. When playing the game, the player should be aware of their *level of calm* by learning how the soundscape changes to reflect it.

Another important goal was to ensure the soundscape was aesthetically fitting within the context of the game; the sound produced from the audio engine should act as the *soundtrack* to the game, encompassing ambience and music, as well as communicating the narrative emotion. It should be intuitive to the player, who must understand when it is shifting in intensity.

The audio engine tested in *Slasher* is split across two applications: Max and FMOD. The audio engine can be further separated into 7 modules, the majority of which are hosted in Max. The audio engine is adaptive because its output changes depending on game-state data; the audio engine adapts to the incoming EEG data *i.e.* the player's *level of calm*.

4.2.1 Max Sound Modules

A control patch was designed to host all five sound modules, handle incoming EEG data transmitted via OSC, and communicate with the Unity game engine. When *Slasher* begins, a message is sent from Unity to the control patch that activates the audio engine. The control patch features individual volume controls for each sound module. Most modules play for the duration of the game.

The *Binaural Beats* module generates independent sine tones in the left and right channel, each with a different frequency. The difference frequency – the *beating* frequency players perceive inside their head – is mapped to the *level of calm.* Due to Brainwave Entrainment, the player's brain activity will begin to match the frequency of this aural stimulus. When fully calm, the difference frequency is 4 Hz which encourages Delta wave activity, reinforcing a relaxed state. When fully agitated, the difference frequency is 30 Hz which encourages Beta wave activity, reinforcing an alert state. Player feedback indicated that the presence of binaural beats made it very difficult to calm down once in an agitated state. This is seen as a success in terms of game design as events in the game impact their emotional state in the real world, thus bolstering the sensation of immersion.

The *Heartbeat* module generates the player's heartbeat, using sine tone generators with pitch and volume envelopes. The heart rate rises and falls with the player's *level of calm*. EEG data is mapped to the delay between successive beats, as well as the timbre and duration of each beat.

The *Electricity* module is used to mimic the sound of the electromagnetic field emitted by the player and detected by the enemy. The module is based on Andy Farnell's example in *Designing Sound* [8]; however, it has been significantly adapted to include resonant frequencies that symbolize the metallic arteries from which the sound originates. The patch uses a multitude of sawtooth wave generators each set to specific frequencies. The output of these generators is controlled by a series of noise gates, creating intermittent bursts of sound. A *buzzing* component outputs frequently, whilst a *sparks* component outputs more sporadically. Intricate mapping of EEG data is featured in this module, with the player's *level of calm* affecting 10 separate parameters of the sound. For instance, the center frequency of a resonant filter increases as the player becomes more agitated, causing a more piercing sound. When the player is agitated, gates stay open for longer, adding sustain to the sound. The overall effect is that when the player is very calm, the emitted sound is infrequent and fairly tame. As the player becomes more agitated, the sound grows in intensity and is almost constant.

The *Ambience* module creates environmental sounds like room tone and wind (the asylum contains many open windows). The crux of the patch features lowpass filtered noise. Cut-off frequencies are dictated by the *level of calm,* falling lower as the player becomes more calm. Noise gates are again used to create *gusts* of wind. A *rumble* component is created by passing filtered pink noise through an overdrive object. Pan position of all components is constantly varied throughout duration.

The *Bell Tones* module uses additive synthesis to create eerie bell-like tones which play for long durations. Effects such as overdrive, reverberation and tremolo are applied, rising and falling in intensity with the *level of calm.* Each bell tone comprises a fundamental frequency with 9 slightly inharmonic partials. Tones are triggered randomly, and multiple tones can play simultaneously. The envelope of each tone (and indeed each individual partial) is varied, however, every tone has a very slow attack and very long overall duration. The overall effect is that when the player is agitated, the tones become piercing (due to lowpass filter cut-off frequencies rising) and exhibit and intense tremolo effect. According to player feedback, this was the joint-most effective sound module.

4.2.2 FMOD Events

Two FMOD events were used to create sound elements which could not be implemented procedurally. Each event features a custom parameter which is related to the *level of calm.* As the parameter moves from a minimum value of 0 towards a maximum value of 1, different elements of each event are automated.

The *Breathing* module simulates the breathing from the player character. It transitions through three levels of intensity in accordance with the *level of calm*. Each level is represented on a different audio track within the event, and the volume of each track is controlled by the custom parameter (which is controlled by the *level of calm*). A multitude of audio samples were recorded using a voice actor, representing different intensities of breathing. Although it is the most simple of all modules, it was rated as the joint-most effective sound module by test subjects.

The *Adaptive Music* module is the only non-perpetual sound module. It is triggered at the beginning of level three and plays until the end of the game. The level is split into two parts: the first features quick-spawning enemies which the player must hold-off using a gun; the second features slow-spawning enemies, which the player can navigate past to the exit door (triggering game completion). Two phases of music were scored, one for each part. The player knows it is safe to move towards the exit door when they hear the second phase of the music.

During each phase, the music loops over a 16-bar sequence, however FMOD's 'multi-sound' objects ensure variation, triggering different samples on each loop. FMOD's transition function was used to create a transition between phases. When triggered, a dedicated 'transition phase' plays, bridging the material used in phase one to that of phase two. The transition is triggered when the player's *level of calm* has been below 0.5 for more than 30 seconds.

In each phase, the mix of instrumentation is mapped to the *level of calm*. When the player is most agitated, the mix features all instruments, playing their most dynamic material. When the player is most calm, the mix features only a handful of instruments, each playing calmer material. Resultantly, the player can listen to the mix of the music to ascertain their *level of calm*. This is an example of vertical re-orchestration. The overall result is a highly adaptive music event which can loop endlessly without repetition and also act as an auditory display for the player.

5 PLAY TESTING

IRB-approved testing with human subjects was conducted in order to evaluate the success of the audio engine, as well as the implementation of EEG technology within a videogame environment. A total of five subjects participated, each of whom spent 5+ hours practicing with the Emotiv EPOC EEG headset prior to testing. This allowed Emotiv's algorithms to fine-tune EEG readings to each subject; each individual exhibits a unique range of brainwave activity.

Prior to gameplay, subjects wore the headset while listening to the adaptive audio engine. They were introduced to each sound module individually, and were instructed to close their eyes and listen to how the sound changes over time. Subjects attempted to change the intensity of the sound modules by altering their psychological state. All subjects became surprisingly adept at controlling the audio engine with their minds, and most were able to ramp their *level of calm* upwards and downwards on command.

5.1 Test Procedure

Testing was conducted in the same location under consistent conditions. Each subject played through the game to completion. Each subject used the same mouse and keyboard and the game was presented on the same Apple Thunderbolt 27" display. The game was run on a late-2013 Apple Mac Pro, with the following specifications: 3.5 GHz Intel Xeon E5 processor; 32GB DDR3 RAM; 3GB AMD FirePro VRAM. Background noise was measured at 52-55 dB(A) on average. Subjects wore Beyer Dynamic DT 250 headphones over the Emotiv EPOC headset.

Upon completion of the game, subjects were given a paper-based survey to complete. Questions attempted to ascertain the effectiveness of individual sound modules in three different categories: understanding, interest, and relevance to the game. In lieu of full documentation of every question, the most significant results can be stated: the *Breathing* and *Bell Tones* modules gained the highest aggregated scores across these three categories.

For each individual sound module, test-subjects ranked each category from 0 to 10, with 10 meaning most effective. A single category could therefore achieve a maximum total of 50, with 5 subjects scoring up to 10 points. A single module could achieve a maximum aggregated score of 150, with 50 points for each category. The aggregated scores do not necessarily paint the full picture, however; for instance, the *electricity* module was unanimously enjoyed, but underperformed in the 'understanding' category. Full test results are available online[1].

6 DISCUSSION

Assessment of the overall implementation largely derives from observing the subject tests, as a measurement of success is hard to quantify with numbers alone. Observation of live gameplay showed what was undoubtedly a highly immersive product. Subjects were as enthralled as they were frustrated, trying to calm themselves down in order to overcome challenges. It was clearly a new type of gameplay experience for them, and one that often caused paradoxical thinking: the success of calming down would trigger a positive psychological reaction, thus causing the *level of calm* to rise back into dangerous territory. It was quite surprising to witness just how effective the EEG implementation was.

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[1] http://jordancraigportfolio.com/#/slasher/

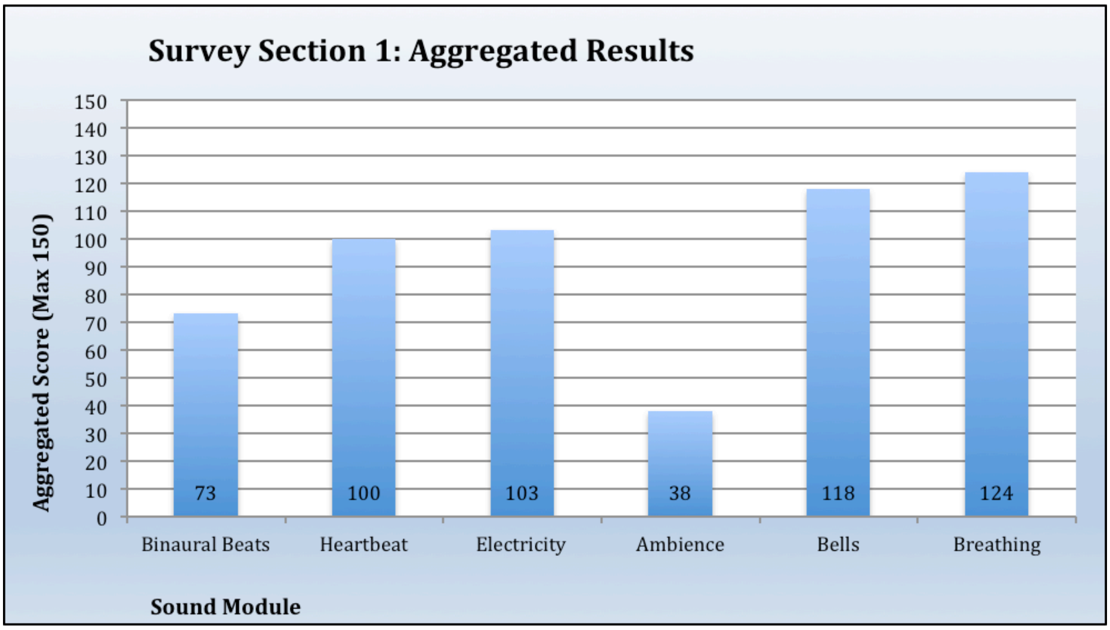

Figure 3 - Aggregate Scores for Sound Modules Rated By Subjects

The overall soundscape created by the adaptive modules was very impressive; again, something that is hard to quantify through numbers and text. Despite some modules overlapping in frequency regions, the general frequency distribution was well balanced. The overall aesthetic of the sound was well-suited to the game. The modules increased and decreased in intensity at similar rates, showing that the EEG mapping was appropriately implemented.

6.1 Future Work

The ultimate goal is to replace the *level of calm* with a *level of fear*. Currently, fear cannot be accurately calculated from EEG data alone. During subject testing, player fear most likely caused increases in the *level of calm* parameter at certain times. This was, however, impossible to test. Extensive work with experts in the fields of psychology and neurology would be required to achieve this 'fear setting'.

Another extension of the work would be to harness multiple EEG parameters, as opposed to one single parameter as was done here. For example, calmness could be mapped to music while frustration is mapped to ambience. Further, the data from each of the 14 electrodes on the Emotiv EPOC could be mapped to 14 different parameters. This would likely result in ambiguity over which psychological reaction was affecting which part of the sound, however, such an application could be fitting for more abstract projects.

Finally, integration with virtual reality is a goal of paramount importance. If it is the game designer's objective to create a highly immersive product, then being able to place the player inside the game both *visually* and *emotionally* is a mouth-watering prospect. Player EEG data could be linked to visual effects, as well as the sonic surroundings, thus tightening the audio-visual bond as well as the overall feeling of immersion. New paradigms of interaction would prompt new methods for audio integration. And while virtual reality lays down roadblocks to the sound designer in the limitations of 3D audio, the implementation presented in *Slasher* offers an alternative avenue to explore.

6.2 Impact on the Field

The field of music technology must be poised for the commercial adoption of EEG technology in videogames. It is a technology that has obvious implications for player control and, to a lesser extent, virtual reality. But the field of music technology must show that audio also has a role to play. EEG data represents a wealth of fluctuating and varying values - the type of values that are very useful in adaptive audio. The work presented here illustrates just one application of its use: a model for using EEG data to drive an auditory display. There are countless other applications, however, and work must be done to explore new areas.

The novel approach exhibited by this project is, in many ways, the first floundering footsteps into a potentially prosperous area for music technology. The ability to match a game's soundtrack to the emotion of the player is enviable. It could become a useful tool for the game designer in communicating various game elements to the player. For example, picture a stealth game in which the player hides in the shadows, using a sniper rifle to eliminate enemies. The player must remain calm in order to aim accurately. This is a fairly common scenario in games and is often illustrated using a crosshair that jumps around sporadically. Imagine instead that the faltering composure is sonified, notifying the player through sound that their shot will likely miss the target. Another application could involve using sound to change the player's emotion based on their EEG reading. For instance, during a horror game, if the EEG reading shows the player is not sufficiently frightened (assuming such emotion recognition becomes possible one day) the sound can change, introducing harsher frequencies and dissonant textures in a bid to unnerve the player.

Work with this emerging technology is still very much in its infancy, thus assessing its current impact is a somewhat recondite task. But the combination of an electroencephalography-based game with an adaptive and procedural audio system provides boundless opportunities of exploration to the sound designer, as well as the game designer. Where EEG prompts new paradigms of player control in games, it must also stimulate new applications of audio. Successful implementation in this manner will engender a slew of immersive products that are highly marketable due to the new type of interaction they offer. A potentially lucrative area lurks on the horizon; the discerning music technologist would do well to be prepared, ready to advance when the market beckons.

7 CONCLUSION

Electroencephalography was used to augment conventional player control over the duration of a survival horror game. The player's psychological reaction to the game directly impacted their performance within it. Successful navigation of the virtual world necessitated the player remain as calm as possible. The thesis put forth was that an adaptive audio engine could be constructed in such a way as to act as an auditory display, informing the player at all times of their *level of calm,* in lieu of visual representation. The overarching impact of such an implementation is that it provides a model for integrating audio with EEG technology in a gaming context.

The adaptive audio engine that was tested comprises seven separate sound modules. Five of these were implemented in Max using procedural audio techniques. The remaining two modules were implemented in FMOD Studio, utilizing its real-time parameter functionality. Player EEG data was transmitted in live time - via OSC - to each module, where it was mapped to various parameters. The overall effect caused the intensity of the soundscape to rise and fall synchronously with the player's *level of calm.* Resultantly, the player could use this auditory display to gauge their performance in the game.

IRB-approved testing was conducted with five subjects, each of whom had previously spent 5+ hours working with the Emotiv EPOC headset. Each subject played the game through to completion while wearing the EEG device. Subject response shows that the adaptive audio engine was successful in communicating their *level of calm* thus aiding in their navigation of the challenges set before them. Specifically, sound modules for 'Breathing' and 'Bells' performed best overall.

The ultimate takeaway from this body of work is that a sophisticated audio system was designed to complement the non-linear world of computer games. As we enter a new age of game design – one which is governed by virtual reality and driven by the demand for augmented experiences - new paradigms of audio application must be relentlessly explored. This project is but one small step in one possible direction.

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