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Multi-sensory environments adaptation for the relaxation of children with neurodevelopmental disorders

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Abstract

Neurodevelopmental disorders are a group of conditions that can arise in the early stages of the development of a child and, depending on the degree of severity, these disorders can affect multiple aspects of the entire life of an individual. Early therapy interventions are fundamental to cure, if possible, the disorders or at least alleviate the consequences. Relaxation can be beneficial to reduce anxiety, tension, potential aggression and improve concentration; it can be achieved using relaxation techniques, requiring in some cases some form of training, or simply listening to music. Relaxing music has been suggested by research studies to have a greater effect if it is not familiar to the patient and if it contains changes in tempo and a limited presence of high frequencies.

The objective of this thesis is to investigate the potentialities of these notions adapting a multisensory environment, created by music and lighting, to the child's state for one of the following goals: relaxation enhancement, training of the child's relaxation abilities, training to handle more musical stimuli. The developed Chrome application is controlled by the relaxation level of the child measured by a cheap MindFlex EEG headset, that also permits to collect data during sessions. The music, programmed by a composer on a separate audio environment implemented using the Web Audio API, uses the concepts of algorithmic music so it can vary, slightly or considerably, at every session. In response to the relaxation value, depending on the definition of adaptation for the goal of the session, the software modifies in real-time some combination of global or instrument-specific characteristics of the played music: volume, tempo and frequency content. Philips Hue lights are used to create an immersive environment expressing the link between sound and color, varying the brightness of the lights to reflect the volume or frequency content of the music through the concepts of chromestesia, a type of synesthetic experience.

Sommario

I disturbi dello sviluppo neurologico sono un gruppo di disturbi che possono comparire nei primi anni dello sviluppo del bambino e, in base al grado di severitá, possono condizionare vari aspetti della sua vita intera. É importante che le terapie per curare, se possibile, questi disturbi o almeno alleviarne le conseguenze siano messe in atto il prima possibile per avere maggiori probabilitá di successo. Il rilassamento é un aspetto che puó portare benefici riducendo ansia, stati di tensione, aggressivitá e migliorando la concentrazione; puó essere raggiunto tramite l'utilizzo di tecniche di rilassamento convenzionali che possono richiedere una prima fase di training, oppure tramite il semplice ascolto di musica. Studi scientifici hanno suggerito che la musica rilassante abbia un effetto maggiore se questa non é conosciuta dall'ascoltatore e se contiene cambiamenti di tempo (inteso come bpm) e una presenza limitata di alte frequenze.

L'obiettivo di questa tesi é quello di studiare le potenzialitá di questi concetti adattando un ambiente multisensoriale, costituito da musica e illuminazione, allo stato del bambino per uno dei seguenti scopi: miglioramento del rilassamento, miglioramento delle abilitá di rilassamento, miglioramento della gestione di vari stimoli musicali. La Chrome application sviluppata é controllata dal livello di rilassamento del bambino misurato da un MindFlex EEG headset che permette anche di raccogliere dati durante le sessioni. La musica, programmata da un compositore in un ambiente audio separato implementato tramite l'utilizzo di Web Audio API, fa uso dei concetti di musica algoritmica per variare, di poco o di molto, ad ogni sessione. In risposta al livello di rilassamento, a seconda di come l'adattamento é stato definito per lo scopo della sessione, il software modifica in tempo reale una combinazione di caratteristiche, globali o specifiche di uno strumento, della musica suonata: volume, tempo e contenuto frequenziale. Un sistema di luci Philips Hue é utilizzato per creare un ambiente immersivo esprimendo la correlazione tra suono e colore, variando la luminositá delle luci per riflettere il volume o il contenuto frequenziale della musica implementando i concetti della cromestesia, un tipo di esperienza sinestetica.

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Chapter 1

Introduction

Music therapy is a wide field especially for the treatment of neurodevelopmental disorders; it comprehends various types of techniques with different goals. Since the importance of the relationship between the therapist and the patient, these treatments don't usually involve technology. That doesn't preclude the possibility of automating some aspects of the therapy taking advantage of the existing technology so the therapist can focus only on the patient. Garzotto, Gelsomini and others [14] automated a treatment based on the concept of adaptation for children with intellectual disabilities: soft music and lights are used to induce relaxation in the patient, the volume is lowered when the patient relaxes to get him used to stay relaxed also when the music is less present and to express a correlation between the child's state and the atmosphere. This treatment, like the others, used to be performed manually by the therapist that estimates the relaxation of the child by his behavior and adjust the music volume accordingly. The automation utilizes an EEG headset to accurately measure the relaxation level and a cloud-based software to handle the music volume and lights, so the therapist can be completely present for the patient without distractions.

My thesis is based on part of this project, starting from the same concept of music therapy and adaptation to expand it towards other possibilities. As the mentioned project, this work uses an EEG headset to accurately measure the relaxation level of a child, and respond to that value changing the environment by the modification of lights and some sound characteristics of the played music. These changes are based on the notion and characteristics of relaxing music and they aim to enhance or train relaxation using adaptation of sound and lighting.

Goals of this project are to find other ways to adapt this multisensory environment, to look into the possibilities of using always slightly new music at every session and to develop an audio environment that enables composers to program this type of music using compositional techniques that are common in relaxing music.

Another goal of this work is to focus on the link between music and color, looking for those correlations in the concepts of synesthesia, to create an immersive experience.

This thesis is organized as follows:

- chapter 2 presents a path through the state of the art to analyze the target user group, the common treatments, the concepts and goals of music therapy, the benefits and measurement of relaxation and the possibility to use music listening to enhance it; the chapter ends with an overview of the use of algorithmic music in the context of relaxation and the considerations that lead to this thesis;

- chapter 3 reports the fundamental concepts about sound and synthesizers needed to understand the work done;

- chapter 4 starts with the design of the user experience based on the user needs, then examine the possible scenarios, the hardware and software technologies used in this project and the software architecture; the chapter then presents the development of a virtual synthesizer, the functions to generate algorithmic music, the real-time functioning and adaptivity of sound and lights, and the concepts behind the relationships between sound and lights;

- chapter 5 draws the conclusions and possible future works to expand this thesis.

Chapter 2

State of the art

2.1 Neurodevelopmental disorders

Neurodevelopmental disorders are a group of conditions that can arise in the developmental period of a child, frequently in the early stages of the development. During those early years the brain is subjected to a wide amount of modifications and changes caused by the continuous stimuli deriving from the environment in which it is growing. Depending on the degree of severity, these type of brain disorders can affect multiple aspects of the entire life of an individual, like emotions, learning ability, self-control and memory, just to name a few. Causes can be attributed to genetic or infectious disease, physical traumas, immune disfunction or environmental factors. Few of these disorders can be almost completely cured, but appropriate early interventions and therapy can alleviate some of the consequences of the chronic ones [13].

Neurodevelopmental disorders include intellectual disability (ID), autism spectrum disorders (ASD) and attention deficit hyperactivity disorder (ADHD) among others.

Intellectual disability is characterized by severe limitations in intellectual functioning and adaptive behavior; it's worth noticing how the definition doesn't mention only the intellectual side of the disorder, but also the relationship with the environment. It affects skills that are fundamental for the everyday life, like social and interpersonal skills, communication, self-care, self-control and basic academic skills like reading or writing. Causes can be multiple, for example metabolic, infectious or chromosomal. Therapy, specialistic support and a good environment are essential to improve the life of the affected person.

Autism spectrum disorders (ASD) are a wide group of developmental disabilities, hence the term "spectrum". Symptoms can vary greatly from child to child, but they usually include serious deficits in communication, behavior and socialization. In details, a person with ASD is characterized by difficulty with nonverbal and verbal communication, difficulty in developing relationships, stereotypical motor or verbal behavior, excessive adherence to routines and ritualistic patterns of behavior and limited interests. The brain of an affected person functions in a different way with respect to other individuals, but also in a different way with respect to other people with ASD. Every child or adult with autism is unique, so therapy needs to be planned for the needs of every single individual and it needs to vary to address the new challenges in the life of the child when he changes environment, for example entering school.

Deficit hyperactivity disorder (ADHD) affects self-control. Three general symptoms are used to categorize the disorder into main overlapping areas: inattention, hyperactivity, impulsivity. Other symptoms can include anxiety, obsessive-compulsive disorder, bipolar disorder and learning difficulties. Since in most cases ADHD co-occur with other disorders, professional support and therapy are essential.

Neurodevelopmental disorders can be categorized into different pathologies as seen above, but there's also a strong overlap across them [52].

2.2 Map of treatments

In the last decades, many support centers has been founded all over the world, places where children can find help in form of treatments based on a professional evaluation and parents can find useful information, training and support. Treatments in centers can be categorized in the following way:

- speech and language therapy addresses those difficulties in speaking and in understanding verbal and non-verbal cues when talking with others. It is designed to coordinate the mechanics of speech with the meaning and social use of language. Moving from a first evaluation about the verbal abilities of the child, the goal may include improving spoken language or learning non-verbal communication (signs and gestures). A type of therapy for non-verbal or very limited verbal individuals uses pictures to help building a vocabulary

- occupational therapy enables the child to learn and enhance fine motor skills needed for daily living, for example dressing, eating, bathing. This therapy addresses a combination of cognitive, physical and motor skills; the evaluation is based on motor skill development, visual motor skills, handwriting, self-help skills. The goal is to help a child gain age-appropriate independence and partecipate more fully in life

- physical therapy focuses on problems with movement that cause real-life limitations. This therapy addresses the challenges in motor skills like running, balance, jumping, sitting, holding objects and walking, improving coordination and muscle tone. Evaluation is based on physical abilities of the child and developmental level

- behavioral therapy minimizes and corrects negative behaviors such as throwing tantrums, refusal to interact socially or hitting others. One of the possible techniques is positive reinforcement: when a behavior is followed by some sort of reward, the behavior is most likely to be repeated

- sensory integration therapy addresses the challenges in processing sensory information such as movement, touch, sound, sight and smell; the evaluation is based on an individual's sensitivities. This type of therapy often uses slides and trampolines matching sensory stimulation with physical movement to improve how the brain processes and organizes incoming information

2.3 Music-based treatments

The concept of using music as a form of therapy was born in the years between the two World Wars when musicians started visiting hospitals to play music for veterans suffering from physical, cognitive and emotional pain [57]. Doctors noticed the positive effect of music on their patients, so hospitals began to hire musicians. After a brief trial period, it was clear that some form of training was necessary for those musicians; the training was focused on how to interact with the patients and how to perform in the hospital for the benefit of the patients. This was the dawn of music therapy (MT) in 1940, but music therapy became a recognized field only in 1996 with a decision by the World Health Organization, although the research, study and practice have never stopped since those first days [9, 41].

Over the years music therapy evolved from listening to music to all the music-based experiences like singing, playing musical instruments, creating or discussing songs. Many types of music therapy have been developed, some of them have been extensively studied and recognized as helpful in some situations, while others are experimental and still lack of proofs. The main types of music therapy are:

- receptive MT involves listening to live or recorded music to cause reactions or emotions in the patient; this was the first type of music therapy
- compositional MT focuses on the process of creating original music
- improvisational MT involves music improvisation performed by the therapist and the patient
- recreative MT focuses on learning to play a musical instrument, including rehearsals and performances
- activity MT merges together music and games in musical structured games

However, in practice a music therapist can use therapies that don't clearly fit in only one of these categories [2].

Other more experimental therapies are controversial and lack of objective proofs of benefits. An example of this type of therapies is the vibroacoustic therapy developed by Olav Skille using the physiological effects of sound vibrations on the body [45]. The audio material used is composed of low frequency sounds of specific frequencies reproduced through subwoofers; the subwoofers are mounted on a chair where the patient sits. A more known treatment is the auditory integration training (AIT): a technique to improve hearing in patients who show some form of noise sensitivity [10] . The audio material used in the therapy consists of music or noise being manipulated with the use of wide band filters that attenuate the volume of a particular band of frequencies. The band of frequencies is randomly chosen every 0.2 - 2 seconds. This results in a listening experience with constant and very fast changes that inspires greater attentiveness to the music but it lacks of positive long term effects.

2.4 Goals of music therapy

Music therapy has been extensively used with children with neurodevelopmental disorders. The literature presents a large number of case studies with single individuals targeting some aspects of the disorders: socialization, communication and behavior.

Socialization Therapy sessions to increase social participation, socialization and eye contact can use shared musical instruments. Starr and Zenker

[46] studied the sharing of a musical keyboard between the therapist and a 5-year-old male with autism reporting positive results: the child particularly enjoyed one of the songs they played, showing improved socializations during it. Saperston [43] focused on improvisational sessions with an 8-year-old male with autism. The therapist associated different gestures on the piano to the various child's movements, for example playing a low G was associated with the movement of the left feet, playing an high G was associated with the movement of the right feet, just to name a few. The child showed improvements in eye contact and socialization with the therapist, smiling when he started to understand how he could influence the music played. A case study by Wimpory, Chadwick and Nash [64] used a similar technique with a 3-year-old child involving the mother in the session: the mother's movements were synchronized with the therapist's playing on the harp to help the child anticipate her actions. The study showed an increase in eye contact and initiations of involvement with the mother.

Communication Therapy sessions to increase communication and language skills may use a technique called "melodic intonation" where the therapist uses simple melodic fragments to intone short sentences tapping the rhythm of the words on the child's body [5]. The goal is to improve the child's understanding of the spoken language. A case study by Hoelzley [19] used the idea of intonation of sentences with the support of a brass instrument. The therapist played short phrases on the trombone and the child was invited to imitate them. This lead the child to sing short melodies, then words and finally pronounce sentences in a normal way. Mahlberg focused on the rhythm of the speech [35] using a tambourine to create rhythmic patterns while talking to improve the child's nonverbal communication, and clapping to music to increase his attention span. Starr and Zenker [46] developed a structured musical game for a child with autism to increase his correct use of pronouns. The child was invited to repeat the sentences pronounced by the therapist using the right pronouns. A drum was used as a reward for every correct sentence.

Behavior To improve the behavior of children with maladaptive behaviors and lessen their anxiety, music and songs have been proved to have positive effects. Starr and Zenker[46] composed a simple original song "Line up" for a 6-year-old child to help him waiting in line. During sessions the therapist sang the songs with the child using visual cues to better explain the various steps involved in waiting in line. His anxiety and aggression associated with waiting decreased. Dancing to music has also been used to lessen maladaptive and self-destructive behaviors [35].

2.5 The importance of relaxation

Targeting a person's anxiety in treatment can lead to positive outcomes as the stimulus for aggression is removed. The frequency of maladaptive behaviors can be reduced with behavioral interventions, but it is likely that maladaptive behaviors are correlated with emotional states such as anxiety or agitation, making treatment more challenging [40]. The main relaxation techniques are [29]:

- focused breathing, involves paying attention to the breathing process while performing deep breathing
- progressive muscle relaxation, requires focusing in on the body, scanning all the muscles in sequence while letting go of the tension
- visualization/guided imagery, uses audio detailed description of a peaceful place, can be seen as mentally being in a special place

All the techniques require little or no training, so they are suitable for individuals with neurodevelopmental disorders [40].

Positive effects of relaxation in individuals (children and adults) with neurodevelopmental disorders have been documented in the literature. In a study Lim [29] reported that the majority of patients with mild intellectual disability forming the group study felt calm and relaxed immediately after the relaxation exercise, and the day after they could concentrate better in school or work. Moreover more than half of the participants felt less angry thanks to the exercise. McPhail and Chamove [16] noted an important reduction of aggression and verbal disruption in ID adults. Lindsay, Fee and others [30] reported an improvement in concentration and attention to tasks in adults with severe ID. Relaxation techniques has been proven to be helpful for people with severe and multiple learning disabilities [18], for autistic [34] and hyperkinetic ID children [12] and ID adult with generalized anxiety disorder [36].

Listening to music as a relaxation technique Music has been proved to have an impact on humans and to influence emotions [58]. Because of its positive effect it is used in various field, for example in sports for motivation, pre-event activation and to increase performance levels [25]. Although music can be often used as a background during relaxation sessions, listening to music can be consider itself a relaxation technique. Relaxation through music listening doesn't require any training or instructions, so it is a technique that has no limitations in its applicability. Music listening has been used in the medical field as an alternative to medication before surgery to reduce patients' anxiety [27, 54, 28]. Preoperative anxiety and fear may influence the process of induction and recovery from anesthesia, moreover music listening has fewer adverse effects than anxiolytic drugs. Bringman [6] studied the difference between the relaxation induced by midazolam, an anxiolytic drug used before surgery, and the relaxation induced by listening to relaxing music. The result showed that patients in the relaxing music group were calmer and more relaxed than patients in the drug group. The positive effects of music listening have been also showed during operations under local anesthesia, when the patient is alert and exposed to anxiety caused by visual and auditory stimuli [49, 65, 59], and in patients with severe illness or injuries in the intensive care unit [26].

Physiological effects of relaxation In most of the mentioned studies, the level of relaxation has been deducted through questionaries compiled by the patients or through external observations about behavior and body posture. It has been proved that relaxation has also some physiological effects on the body; Loomba, Arora and others [31, 47] reported a great decrease in systolic blood pressure, diastolic blood pressure and heart rate in hospitalized pregnant women during relaxation through music listening. The same effects have been observed in patients with anxiety, pain, depression and sleep-related problems [55]. These parameters can be used to accurately measure the level of relaxation, avoiding subjectivity in the judgement. Relaxation has been proved to also have effects on the brain, having an influence on the brain waves [32, 51, 8, 15]. The brain waves can be measured with an Electroencephalography (EEG), a non-invasive measuring method to record electrical activity of the brain, so an EEG is a valid method to estimate the level of relaxation [1].

2.6 Algorithmic music for relaxation

In most of the analyzed types of music therapy, the music used during sessions is a standard soft song or instrumental composition. Instead, some improvisational music therapies make use of music improvised in real-time by the therapist [43]. The characteristics of this music are linked to the state of the patient and his behavior. This is an example of music that varies in response to some inputs, in this case the state and behavior of the patient. The changes can be applied to strictly musical aspect, as melodies, chords and rhythm, or to sound aspects, as the loudness of the notes. This link between inputs and music has the possibility to create a more immersive experience and can be used for various purposes. Many researchers have used this concept to build apps focused on relaxation using algorithmic music, i.e. music that is composed through formal set of rules or algorithms. This type of music can use user inputs to influence music creation or some aspects of the sound, or it can be completely non-interactive.

Brian Eno, one of the most important ambient artists, collaborated with the Montefiore Hospital for a sound installation that generate non-interactive algorithmic music in a room where patients can find relaxation and calm. Sysoev, Chitloor and others [48] created "Middie Mercury", an interactive ambient music generator conceived as a tool for reducing stress in everyday life. The software generates music in real-time based on how the user interacts with the visuals, correlating notes and chords to specific behaviors of the visuals. MIT Media Lab teamed up with the band Marconi Union to create the app "Unwind" [3] that generates always new relaxing algorithmic music, using the heart rate of the user as tempo for the composition.

2.7 Considerations

Music is a universal tool that has had an unquestionable importance in every culture [44]. Research findings indicates that the social deficits of people with neurodevelopmental disorders may increase the importance of music [17] in the context of music therapy [62, 63] and as self-management for depression, mood change and social affiliation in everyday life [4, 39, 38]:

> "music is the regulator of my nervous system, the shelter for my frezzled mind"[1].

From the analyzed literature, some considerations can be made. First of all, the concept of relaxing music seems to be quite wide and subjective. The music used during music therapy sessions focused on listening is part of a large range that includes classical music, new-age music and soft pop music. The most important characteristic is the tempo: various studies explicitly used music at 50/60 bpm [21, 11, 6], a tempo that imitates the human heart rate at rest [20]. In the community of music therapists the importance of variations of the tempo has been underlined [56, 20] slowing down the music when the listener starts to relax to enhance relaxation. This concept of the

[1] Words by the autistic poet Craig Romkema [42].

variation of tempo could be extended to other parameters manipulating the music to make it more relaxing when the listener starts to feel relaxed.

Another common characteristic in the music chosen for this purpose is the presence of long notes and the limited amount of high tones because high frequencies tend to stimulate more with respect to low frequencies [56]. These are some common aspects, but in some studies researchers let patients choose the music they find relaxing, giving a strong importance to personal taste and listening habits. This seems to be a reasonable motivation but some researchers pointed out the importance of avoiding known music because it could be related to life memories and past emotional states [53] , and moreover a study demonstrated that actually an unknown music can have a greater effect in stress reduction with respect to music selected by the patients [24].

The system used to reproduce the relaxing music seems to have nearly zero importance in the literature. Only few studies mention the use of headphones or speakers, but without providing details. There can actually be no difference in results, but a research paper by Andersson and others [33] raised the question. The experiment was trying to demonstrate if the vibroacoustic therapy [45] had actually some benifits on children with autism and neurodevelopmental disabilities. Vibroacoustic therapy, as briefly presented earlier, is one of those several experimental therapies that have little or no actual scientific proof; it uses specific low frequencies played through subwoofers[2] to cure specific conditions. Andersson and the team didn't use those specific low frequencies, but just used music played through subwoofers noticing improvements in relaxation of the patients stating that "music with felt vibrations has a relaxing effect that can possibly relieve anxiety and discomfort". The mentioned "felt vibrations" that can enhance relaxation are seen as a sound massage and can only be reproduced using subwoofers; headphones or small speakers don't have that capability. Moreover, since low frequencies tend to have more relaxing power with respect to high frequencies, the choice for a suitable audio system for music therapy sessions should incorporate this findings.

As seen in apps for everyday relaxation, there's a strong tendency to play always new relaxing music. There's no precise motivation explained in the literature for it, probably it comes from the observations about the efficacy of unknown music with respect to an already very well known composition and from the observations of the British Academy of Sound Therapy that claims that while listening to music the brain shuts off when it's unable to

[2]Subwoofers are speakers designed to accurately reproduce only low frequencies; they are part of an audio system.

predict what's coming next [56]. Following this assumption, when it comes to a specific composition, the inability to predict the future can be eliminated with the presence of non repeating melodies; instead, the prediction caused by already knowing a piece of music can be avoided using always slightly different music. The use of stochastic algorithmic music could implement both these solutions.

These are some general concepts about relaxing music, they are not specific to how children with neurodevelopmental disorders perceive music. In fact Kalas studied the relation between music complexity and the behavior of children with autism [22]. The results showed that the complexity of music should be tuned with the child's range of functioning: simple music with clear and predictable patterns is the optimal choice for children in the severe range, while more complex and variable music may be most effective for children in the moderate range of functioning. This information should be considered to implement a software capable of generating music for children in every range of functioning.

Chapter 3

Background concepts

Synthesizer A synthesizer is an electronic musical instrument born in the 1960s. Although the journey towards the nowadays concept of synthesizer started many years before, this instrument has been extensively used in commercial music only since the 1980s after manufacturers like Moog, Yamaha and Roland started selling affordable models.

(a) (b)

(c)

Figure 3.1: *Some famous synthesizers from the 70/80s: Moog Minimoog (a), Yamaha DX7 (b), Roland Jupiter-8 (c).*

Most synthesizers are played using a piano keyboard that can be part of the instrument itself or can be a separate controller device. In this case the instrument is called "expander" and it exchanges information with the controller device through a cable; the most used protocols are MIDI, USB and CV/gate.

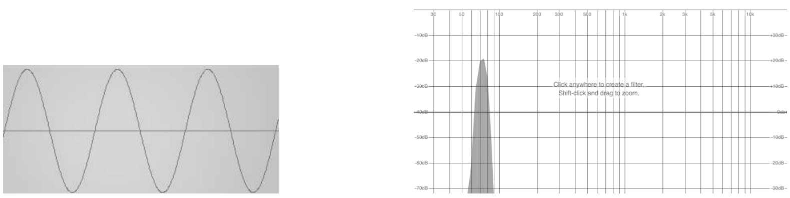
The signal routing system can be totally configurable by the player, as in modular synthesizers, or it can be semi-modular or fixed like in the majority of synthesizers.

Until the end of the 1970s, synthesizers were analog instruments that used operational amplifier integrated circuits and potentiometers to generate and manipulate sound. In 1974 Yamaha was the first manufacturer to develop a prototype of a synthesizer using a digital synthesis algorithm. Digital synthesizers became really popular and that lead to the rapid decline of the analog synthesizer technology, although nowadays it is coming back thanks to the strong appreciation for the classic analog sound. In 1996 Steinberg released a revolutionary technology called Virtual Studio Technology (VST), that was the birth of software synthesizers. Software synthesizers are computer programs or plug-ins that generate digital audio; they can be implemented from scratch to develop new concepts of synthesizers or they can emulate old synthesizers that are no longer manufactured. Thanks to the few limits of computers and to the cheap price, software synthesizers are the most popular and the most used type of synthesizers.

Before presenting the techniques used by synthesizers to create timbres, it is necessary to have a quick overview of the basic building blocks that are needed to generate and manipulate sound: oscillators, filters and envelopes.

Oscillators Oscillators are components that produce sound through the continuous repetition of a waveform. The basic waveforms are:

- sine wave, it produces a pure sound that has no harmonics[1]

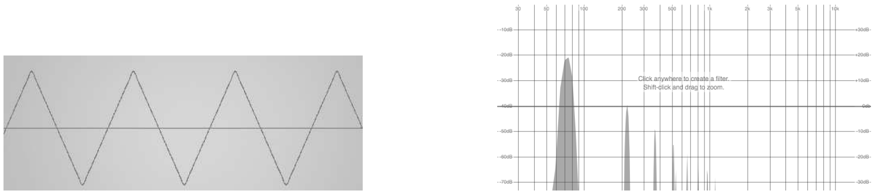


(a) (b)

Figure 3.2: *Sine wave: oscilloscope (a) e spectrum (b).*

- triangle wave, it produces a sound similar to the sine wave but it has only odd harmonics with exponentially decreasing amplitude

[1]Harmonics are integer multiples of the fundamental frequency of the wave.



(a) (b)

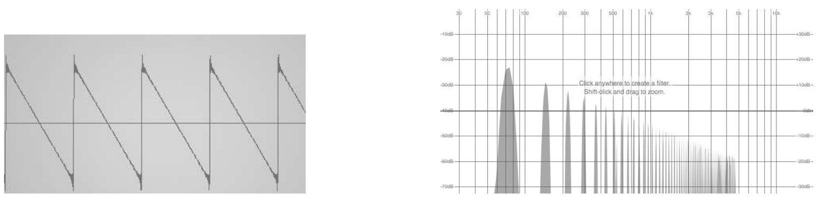
Figure 3.3: *Triangle wave: oscilloscope (a) e spectrum (b).*

- square wave, it produces a sound similar to the triangle wave because only odd harmonics are present but their amplitudes decrease linearly, so the resulting sound has more high frequencies with respect to the triangle wave

(a) (b)

Figure 3.4: *Square wave: oscilloscope (a) e spectrum (b).*

- sawtooth, it produces a sound very rich in odd and even harmonics with linearly decreasing amplitudes



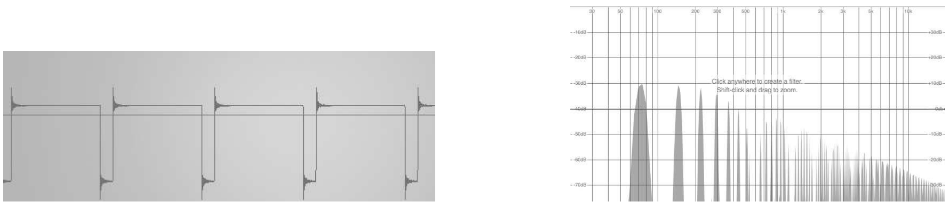
(a) (b)

Figure 3.5: *Sawtooth wave: oscilloscope (a) e spectrum (b).*

- pulse, it produces a sound that has odd and even harmonics but they have different amplitudes; the structure of this waveform can be varied modifying the pulse width to obtain a sound that can be bright or nasal

(a) (b)

Figure 3.6: *Pulse wave: oscilloscope (a) e spectrum (b).*

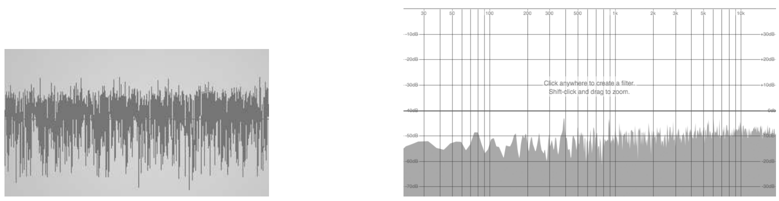


(a) (b)

Figure 3.7: *Pulse wave: oscilloscope (a) e spectrum (b).*

There are different types of generated noise depending on the spectral content:

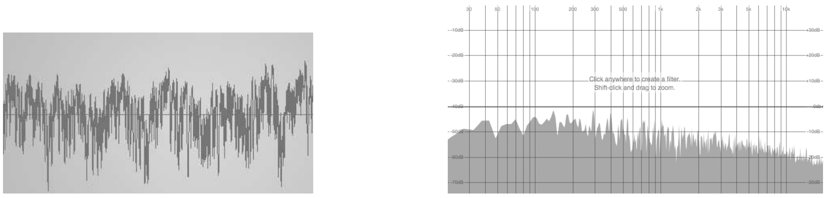
- white noise, it has constant amplitude on every frequency of the spectrum



(a) (b)

Figure 3.8: *White noise: oscilloscope (a) e spectrum (b).*

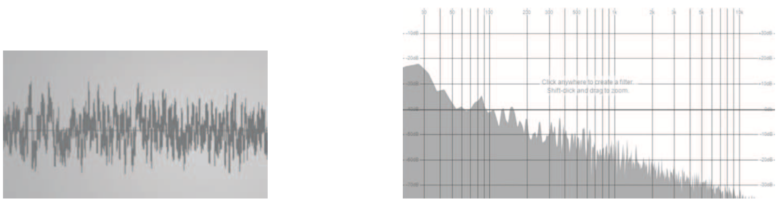
- pink noise, it has more energy at lower frequencies



(a) (b)

Figure 3.9: *Pink noise: oscilloscope (a) e spectrum (b).*

- brown noise, it is similar to pink noise but it has even more energy at lower frequencies.



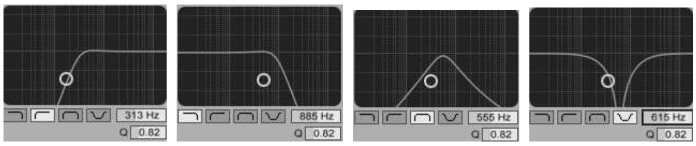
(a) (b)

Figure 3.10: *Brown noise: oscilloscope (a) e spectrum (b).*

Filters Filters are components that manipulate the spectrum of a sound to change its timbre by enhancing or attenuating a certain frequency band. There are different types of filters:

- low-cut filter, it only passes frequencies greater than a certain cutoff frequency, it's also called high-pass filter
- high-cut filter, it only passes frequencies lower than a certain cutoff frequency, it's also called low-pass filter
- band-pass filter, it only passes frequencies within a certain frequency range
- notch filter, it's the opposite of a band-pass filter, it only rejects frequencies within a certain frequency range

Every filter has two parameters that further describe its behavior: the frequency response and the Q factor. The frequency response indicates how the filter attenuates frequencies outside the passing range in terms of slope (12dB per octave, 24dB per octave,etc); the Q factor indicates how much the frequencies close to the cutoff frequency are emphasized.



(a) (b) (c) (d)

Figure 3.11: *Types of filters: high-pass (a), low-pass (b), band-pass (c), notch (d).*

Envelopes Envelopes describe how a specific parameter of a sound change over time. The most basic envelope in synthesizers is the ADSR that describes how the amplitude of a sound change. The acronym ADSR comes from the four steps that describe the envelope: attack (A), decay (D), sustain (S), release (R). The attack time is the time taken by the sound to go from amplitude zero to maximum amplitude when a key is pressed, the decay time is the time taken to go from peak amplitude to the sustain level, the sustain level is the level of the sound until the key is released, the release time is the time to go from the sustain level to zero amplitude when the key is released. Another possible envelope usually present in synthesizers is the filter envelope; it has the same behavior of the ADSR envelope but it describes the behavior of the filter.

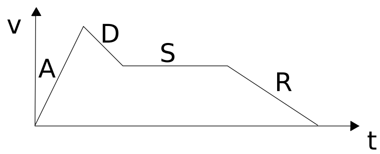


Figure 3.12: *ADSR envelope.*

Sound synthesis There are many different techniques used to design a sound; historically the most important ones are:

- additive synthesis, it was the first method developed because of the simplicity of the concept behind it; it's based on the sum of simple sound waves to create a complex sound wave. The idea comes from the Fourier's analysis theorem: every sound can be decomposed in a set of simple sine wave; so it's possible to obtain every possible sound from a set of simple sine waves. The pipe organ is a perfect example of this technique since every pipe produces a simple sound and pipes are played together to obtain a richer sound. This method seems really powerful in theory, but it needs a large number of data since every simple sound wave has its own parameters and envelopes, and it needs an almost infinite number of simple sound waves to actually create a large number of timbres. For these reasons this technique is rarely used in commercial products.

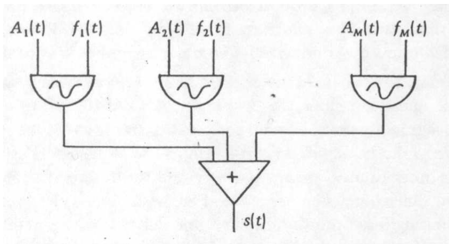


Figure 3.13: *Additive synthesis.*

- subtractive synthesis, it can be seen as the opposite of the additive synthesis since it starts from a complex waveform and processes it through one or more filters to shape the timbre. This technique became very popular in the 1950s, the early days of sound experiments, since it made possible to obtain great results in a shorter time with respect to additive synthesis. In those years oscillators were big and expensive machines that were available only in some research centers, so to create sound using additive synthesis it was necessary to record and overlap a large number of recordings; subtractive synthesis instead just needed an oscillator capable of producing a complex sound wave, a filter to process it and an amplifier to shape the amplitude envelope. The filters used in this technique usually have the possibility to change their parameters over time using an envelope. Examples of subtractive synthesis can be heard for example in brass instruments when played using a mute; a mute is a device that modifies the timbre of the instruments acting as a filter, removing part of the spectral components of the sound.

Figure 3.14: *Subtractive synthesis.*

Other worth mentioning techniques are frequency modulation (FM) synthesis, sample-based synthesis, wavetable synthesis, physical modeling synthesis and granular synthesis.

Chapter 4

Development

4.1 UX design

The target user groups for this project consist of children with neurodevelopmental disorders, therapists and composers. Each one of these user groups has different needs and interact with the application in different ways.

Child UX and needs The child uses an EEG headset as a brain-computer interface (BCI). Usually BCIs are used as an active way of controlling an application, so the user for example intentionally tries to focus or relax to change some parameters in the application. This is the common paradigm for BCIs and it's been widely used in softwares and in interactive installations. The opposite paradigm has been used in this project and it's called *passive brain-computer interface*. The software is intended to respond to the unintentional variations of the relaxation level of the child. In this paradigm the user has no active task to perform, the application adapts itself to the state of the user who is immersed in an always changing environment on which he has unintentional control.

Playfulness and comfort are really important for the child experience so they need to be taken into account; the headset can be inserted in a colorful and fun helmet (figure 4.1), and the therapist can wear a matching helmet so the child feels more at ease while wearing it. The room chosen for the sessions needs to be a simple and non-overstimulating environment since children with neurodevelopmental disorders may present difficulties dealing with too many stimuli.

Figure 4.1: *UX child: Helmet.*

Therapist UX and needs The therapist controls the application through a classic user interface made of buttons, switches, dropdown menus and other visual elements. Important aspects are the gathering of data during sessions and the possibility to save data for post-session analysis. A visual feedback about the child's state can be useful, but it needs to be as simple as possible to permit quick looks that don't take the attention away from the patient. Change of settings should be minimal and, if possible, done only at the beginning of the session to avoid actions that could be distracting for the child.

The user interface is organized in panels for a better visualization; the panels are dynamic so they can be collapsed or hide to not show parts of the interface and make space for the controls that are most needed in every moment. When the therapist runs the application, he's guided during the basic settings to make the user experience fluid and straightforward: the user interface shows only the first configuration about selecting the serial port used in the connection to the headset, after that the interface changes showing the module to select the file containing the username needed for the connection to the lights, then the other modules appear to build up the full user interface for the therapist.

The "music maker" module contains the button to upload a music composition JSON file and some general optional controls for the selection of the scale of the composition, for the selection of the volume, in case the volume of a music composition needs to be adjusted, and for the bpm of the music, in case the therapist wants to experiment with different tempos for the same music composition. The play and stop buttons for the music are also included in this module.

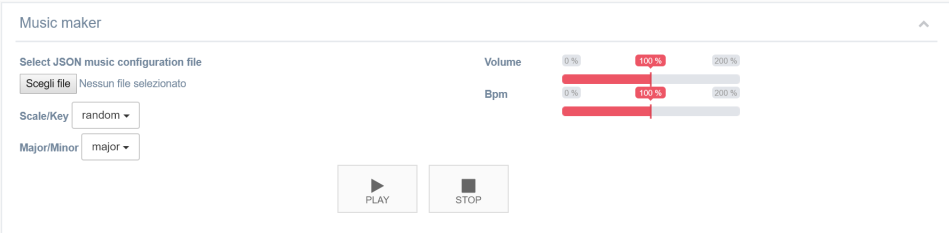


Figure 4.2: *UX therapist: Music maker module.*

The "data reading" module contains two graphs: the first one represents the attention and relaxation levels measured by the headset, the second one shows how the parameters of music and lights are changing (in response to the level of relaxation of the child).

Figure 4.3: *UX therapist: Data reading module.*

The "adaptation" module is the core of the application, it contains all the settings to define the adaptation selecting how the music and lights change in response to the relaxation level of the child. Three parameters of the music can change: the volume, the tempo (bpm), the frequency content (obtained using a filter). The adaptation can be turned on and off using switches. For every parameter an adaptive function needs to be selected, this function dictates how fast the parameter varies with respect to the relaxation level: in a linear way, in a quadratic way or following a long-term trend measured by the weighted mean of the last 30 relaxation values. These changes can be in the same direction of the relaxation level (direct) or the inverse. The bpm parameter is for definition a global parameter of the music, while volume and spectral content can be both global or defined for a single instrument. So other controls make it possible to select "global" or one of the instruments present in the music piece so the adaptation is applied only to the parameter of that single instrument leaving the rest of the composition unchanged. The intensity of the lights can follow the changes of the volume or the timbre to enhance the immersivity of the experience. The color is fixed and can be selected between a list of warm colors that enhance relaxation[1]. For simplicity of use, buttons to recall presets of these adaptation settings are included, one for each possible usage scenario explained in the next section.

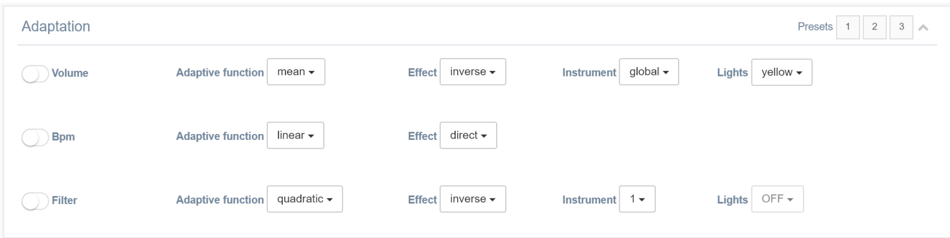
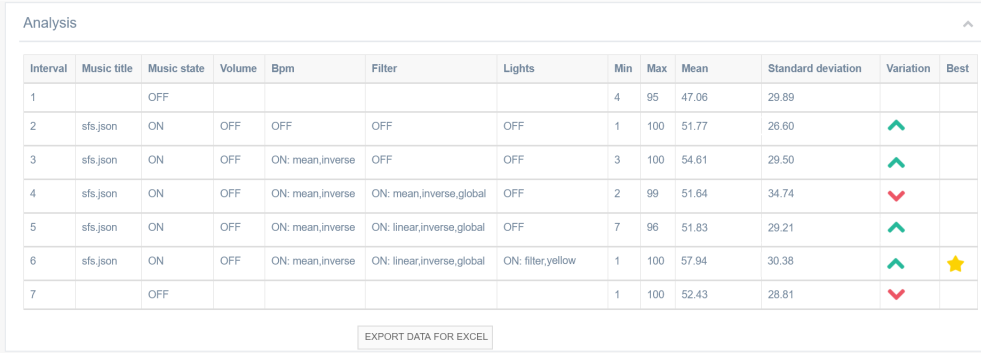


Figure 4.4: *UX therapist: Adaptation module.*

The last module is the "data analysis" module (figure 4.5), it contains a summary table with useful information about how the used settings had an impact on the relaxation level of the child. An interval is defined as a period of time where the adaptation settings remained untouched, so a new interval starts every time the adaptation settings are changed. When a new interval starts, a new row is added to the table; this new row contains information about the current interval. Every 60 seconds the row is updated to add some statistical measures of the relaxation of the child. When the interval ends, some icons are added to summarize how the relaxation is changing over the intervals using arrows to indicate the incremental variation in relaxation level with respect to the previous settings and a star icon representing the interval with the best relaxation level. At the end of the session, this table is exported and stored as an Excel data sheet.

Composer UX and needs To program the music the composer needs a different interface; a separate application has to be developed, intended to be used only by the composer to program the music script. This interface needs to use concepts and a lexicon composers are familiar with and ways to preview the programmed music during the creation.

[1]See section 4.5 for details and motivations.



Interval	Music title	Music state	Volume	Bpm	Filter	Lights	Min	Max	Mean	Standard deviation	Variation	Best
1		OFF					4	95	47.06	29.89		
2	sfs.json	ON	OFF	OFF	OFF	OFF	1	100	51.77	26.60		
3	sfs.json	ON	OFF	ON: mean,inverse	OFF	OFF	3	100	54.61	29.50		
4	sfs.json	ON	OFF	ON: mean,inverse	ON: mean,inverse,global	OFF	2	99	51.64	34.74		
5	sfs.json	ON	OFF	ON: mean,inverse	ON: linear,inverse,global	OFF	7	96	51.83	29.21		
6	sfs.json	ON	OFF	ON: mean,inverse	ON: linear,inverse,global	ON: filter,yellow	1	100	57.94	30.38		
7		OFF					1	100	52.43	28.81		

Figure 4.5: *UX therapist: Data analysis module.*

The user interface is built around a global module (figure 4.6) containing general information like the script name, the bpm of the composition and the default musical scale, and one or more instrument modules (figure 4.7), one instance for every instrument of the composition. In this module it is possible to set up a new instrument inserting the parameters about its sound, and program how the instrument will perform in the composition using stochastic functions or defined values[2], to program music suitable for children of every range of functioning. Loops can be programmed to implement the concept of sonic mantras: repetitive patterns that in the context of relaxing music are useful, having the role of traditional meditation mantras. Some other functionalities are necessary: a button to preview the sound and the performance of a single instrument, a button to preview the total composition and a button to export the settings in a JSON file.

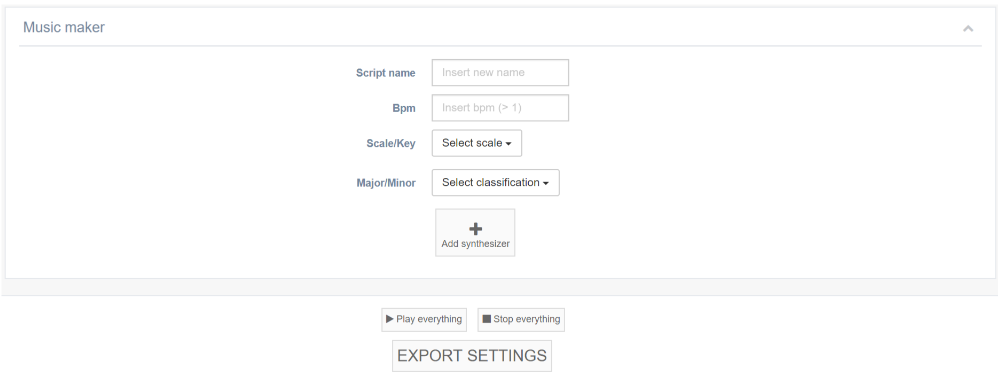


Figure 4.6: *UX composer: Global module.*

[2]See section 4.4 to understand the parameters to program the instrument and the composition.

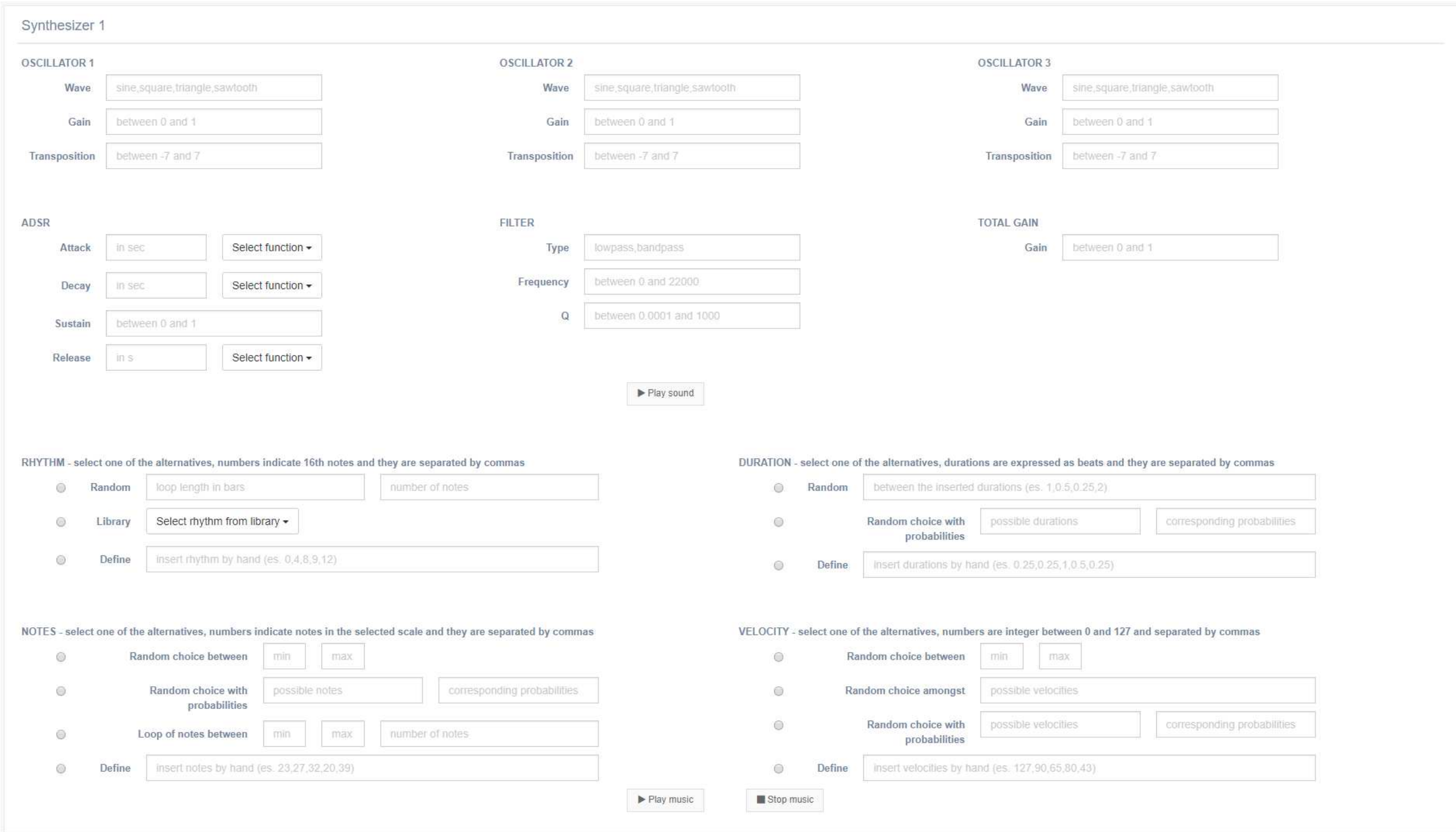


Figure 4.7: *UX composer: Instrument module.*

4.1.1 Scenarios

4.1.1.1 Relaxation training

This first scenario is based on the work of Garzotto, Gelsomini and others [14].

Persona : therapist, child with neurodevelopmental disabilities

Tools in use : MindFlex EEG headset, computer (running Chrome browser), audio system, Philips Hue lights set

Goals : relax the child and improve his everyday relaxation abilities

Music adaptability settings : global volume adaptation with inverse effect

Process : the child sits or lies down in a comfortable position, the therapist helps him wear the helmet containing the EEG headset and wears a matching helmet, runs the application, sets up the settings and asks the child to relax. Then the process can be examined in successive steps called intervals: in the first interval the music and lights are off to gather some information on the relaxation level of the child, then the therapist plays the music without activating any adaptation to understand if the music helps the child relax, if so global volume and lights adaptations can be activated, otherwise another music composition can be played. During the session, when the child starts relaxing the music will gradually lower its volume so the child gets used to stay relaxed also when the music is present with low volume; the lights follow the music so the whole ambience will gradually fade out when the child is relaxed. If the child loses relaxation, the whole ambience will fade in to help the relaxation again. The therapist can quickly glance at the data analysis section to understand how the mean relaxation level of the child varies. When the session ends, the therapist exports and store the data analysis table as a data sheet for further analysis and future reference.

4.1.1.2 Relaxation enhancement

Persona : therapist, child with neurodevelopmental disabilities

Tools in use : MindFlex EEG headset, computer (running Chrome browser), audio system, Philips Hue lights set

Goals : relax the child and enhance the relaxation power of the music to guide him into a deeper relaxation manipulating it by slowing down the tempo and/or filtering out the high frequencies

Music adaptability settings : tempo adaptation with inverse effect and/or filter adaptation with inverse effect

Process : after the initial preparations common to the first scenario, the therapist asks the child to relax. In the first interval the music and lights are off to gather some information on the relaxation level of the child, then the therapist plays the music without activating any adaptation to understand if the music helps the child relax, if so the presented music adaptation settings and lights can be activated, otherwise another music composition can be played. During the session when the child starts relaxing, the music will gradually become more relaxing to improve the effect on the child and guide him towards a deeper relaxation; the lights follow how the music changes to keep a link between the behavior of sound and lights creating an immersive environment[3]. As in the other scenarios, the therapist look at the data analysis section to understand how the mean relaxation level of the child varies. When the session ends, the therapist exports and store the data analysis table as a data sheet for further analysis and future reference.

4.1.1.3 Training to handle more stimuli

This is a potential idea for treatment that was born while studying the various possible combinations of adaptation settings. In one setting, the software can vary the volume of one instrument to introduce it gradually when the child relaxes and remove it as soon as the child becomes less relaxed. Since many children with neurodevelopmental disorders display difficulties in handling multiple stimuli at the same time and music complexity, these settings could be used to improve the ability to handle more musical stimuli inside a relaxing environment. In a future extension this scenario could be used to gradually introduce into the music an instrument that plays everyday noise (e.g. traffic or alarm sound) to help the child get used to a specific sound in a relaxing situation.

Persona : therapist, child with neurodevelopmental disabilities

[3]See section 4.5 for details and motivations.

Tools in use : MindFlex EEG headset, computer (running Chrome browser), audio system, Philips Hue lights set

Goals : relax the child and improve his ability to handle multiple stimuli

Music adaptability settings : volume adaptation of a single instrument with direct effect and/or filter adaptation of a single instrument with direct effect

Process : after the initial preparations common to all the scenarios, the therapist asks the child to relax. In the first interval the music and lights are off to gather some information on the relaxation level of the child, then the therapist plays the music without activating any adaptation to understand if the music helps the child relax, if so the music adaptation settings and lights can be activated, otherwise another music composition can be played. During the session when the child starts relaxing, an instrument will gradually become more present and will gradually fade out as soon as the child loses relaxation; the lights follow the behavior of that single instrument keeping a link between the behavior of sound and lights to create an immersive environment[4]. As in the other scenarios, the therapist look at the data analysis section to understand how the mean relaxation level of the child varies. When the session ends, the therapist exports and store the data analysis table as a data sheet for further analysis and future reference.

4.2 Technologies

Hardware technologies An electroencephalography (EEG) headset is used to measure the level of relaxation of the child. An EEG headset is a tool that can read the electric activity of the brain using electrodes placed on the head. The complexity of headsets goes from simple single-contact devices to more precise and expensive 16-contact devices. The brain signals measured by EEG headsets are called brain waves, they are categorized with respect to their frequency; their intensities vary according to the state of the brain:

- delta waves, signals with frequency between 0.1-3 Hz, strong during deep states of sleep
- theta waves, signals with frequency between 4-7 Hz, strong during REM sleep

[4]See section 4.5 for details and motivations.

- alpha waves, signals with frequency between 8-12.5 Hz, strong during wakeful relaxation with closed eyes
- beta waves, signals with frequency between 12.5-30 Hz, strong during normal waking consciousness and active concentration
- gamma waves, signals with frequency between 32-100Hz,strong during simultaneous processing of information from different brain areas

The majority of EEG headsets measure the brain waves and process that information with proprietary algorithms to estimate some high level features like the attention level, relaxation level, mental effort, emotions, stress level and blink detection.

The headset chosen for this project to measure the relaxation level of the user is a modified version of the wireless headset that comes with the game MindFlex by Mattel. MindFlex is a commercial game that uses a cheap headset, an obstacle course and gentle streams of air; when the player is focused, a small foam ball is raised by the streams of air and moved through the course; when the player is relaxed, the ball descends. The headset is a single-contact device that uses earlobes as electrical ground and has the same chip as the MindSet by Neurosky.

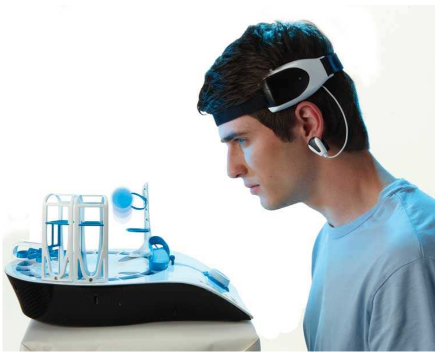


Figure 4.8: *MindFlex game.*

The choice for this particular headset was based on its cheapness, since it makes it easily affordable. Because of this reasons, various hacks have adapted the MindFlex headset to work with software applications using Arduino or a Bluetooth chipset. Through this hacks the headset enters a special mode to output not only the attention and relaxation values but also the intensity of the various brain waves.

The headset used in this project has been modified integrating a Bluetooth chipset that enables the communication with computers and smartphones. The library Cylon Mindflex has been recently developed by a group

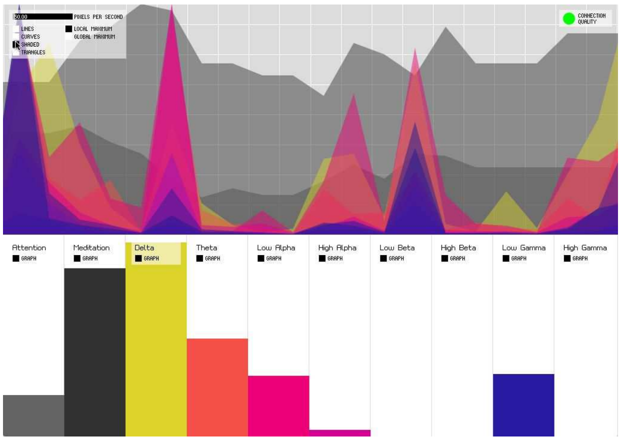


Figure 4.9: *Output of the MindFlex headset in an Arduino hack.*

of students at Politecnico di Milano [14] to use this headset in a Chrome Extension application.

Another hardware technology used in the project is the Philips Hue: a moderately cheap and modular wireless LED lighting system, that will be presented in section 4.5.

Software technologies Since the potentialities for treatment centers for neurodevelopmental disorders to have web-based systems and the potentialities of portability [14], the software was intended to be a web-based application. The project was developed as a Chrome Extension to be installed in a Google Chrome browser; the Chrome APIs made it possible to communicate with serial devices, the Web Audio API made it possible to implement a complex audio application in the browser[5]. Thanks to these technologies, the software can be used in centers of every size that has minimum equipment or it can be adapted to be part of the web-based software architecture of larger centers. The software used only by the composer can be a simple webpage, since it can be separated from the main application and it doesn't need to communicate with the headset.

The main programming languages used were HTML and Javascript. HTML was used to code the user interfaces of both the main application and the composer panel, making use of the Bootstrap framework for a responsive design and the Amcharts library for the graphics. Javascript was used to code the rest of the software making use of the Cylon Mindflex library to implement the communications with the EEG headset and the Web Audio API to handle the sound. The library uses Node.js to have an asynchronous system

[5]Web Audio API will be presented in section 4.4

with better performances so, since the software runs on a browser, Browserify is needed to merge all the Javascript files and remove the dependencies from Node.js.

4.3 Software architecture

As seen earlier in the UX section, two separate softwares are needed: one for the main application and one just for the composer. The main application is a Chrome Extension and it has to deal with the connection of the headset, the gathering and visualization of the EEG data, the loading and playing of the music composition file, the music and lights adaptation, and the data analysis. The main software is composed by the following modules:

- manifest.json describes the application and specifies the script to launch when the application is opened
- background.js is the script specified in the manifest that opens the HTML main page
- UI.html is the main HTML page opened by the background script
- musicmaker.js contains the audio environment
- music-scale.js deals with the generation of musical scales for the composition, once the musical scale has been selected this module fills an array with only the notes of the selected musical scale
- headsetReceiver.js, adapter.js, cylon-mindflex library, browser-serialport library implement and handle the connection and communication with the headset
- UI.js is the main core of the application, it handles the user interface and manage the other managers: sessionStarter.js, FollowingTask.js, LightsFollowingTask.js and dataReceiver.js
- updateUI.js only deals with the update of the user interface when a new music file is loaded
- control-panel.js contains the initialization of the EEG graphs
- view.js is the manager of the EEG graphs and the music and lights adaptation
- dataManager.js handles the data analysis table

On the contrary the software for the composer is quite simple, it consists of a webpage (composer-panel.html), a module that handles the user interface (view.js), an audio environment (composer-panel.js) and a script for the generation of music scales (music-scale.js).

4.4 Sound

4.4.1 Web Audio API

The Web Audio API is a high-level JavaScript API for processing and synthesizing sound in web applications. Before its development, audio on the web had to be delivered through plugins like QuickTime and Flash. The "audio" element in HTML5 brought some improvements allowing for basic streaming audio playback, but more complex interactive applications and web-based games needed a different and more powerful solution.

The API is based on AudioNode objects; they are the basic building blocks and they are divided into categories:

- audio source
- audio destination
- intermediate processing module

AudioNodes have inputs and outputs; the number of inputs and outputs define the category of the object: audio sources have zero inputs and one or more outputs, audio destinations have no outputs and one or more inputs, intermediate processing modules have one or more inputs and one or more outputs so they read the inputs, do some processing that depends on the specific object and generate the outputs. The AudioNode objects are meant to be connected to create a modular audio routing graph that usually matches the following paradigm, where the audio context represents the processing graph.

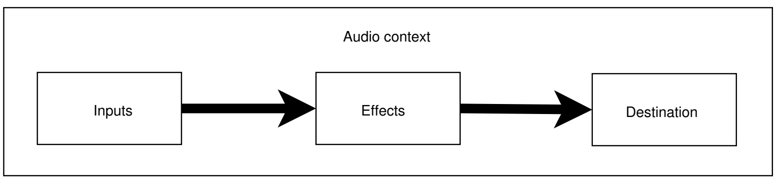


Figure 4.10: *Audio routing graph paradigm.*

The graph can change its structure while the web application is executing.

Audio sources can generate sound from scratch as oscillators do, or they can be audio streams or audio buffers. Processing modules can control volume or apply effects to the input sound such as reverberation[6], filtering[7], compression[8], panning[9] and others. Audio destinations in standard applications are usually the system speakers.

A simple example of a modular audio graph is illustrated in the following picture.

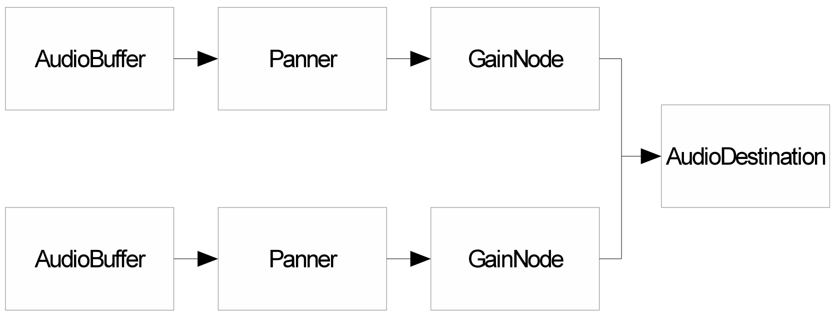


Figure 4.11: *Audio routing graph example.*

Here two AudioBuffer objects acts as inputs that are processed by the Panner and GainNode objects and reach the final AudioDestination. The scheme represents an audio context where two sound files are played separately, and there's the possibility to control the sound location (thanks to the Panner) and volume of the two sources (thanks to the GainNode).

Web Audio API has been used in a variety of web applications, here are some examples:

- guitar tuner, it uses the computer's microphone as input and determine and visualize the frequency being played on the guitar

[6] A reverb, in its simplest form, imitates the effect of a room on a sound source playing inside it.

[7] A filter changes the timbre of a sound.

[8] A compressor changes the dynamic of a sound.

[9] A panner changes the sound location, in its simplest version the extremes are left speaker and right speaker.

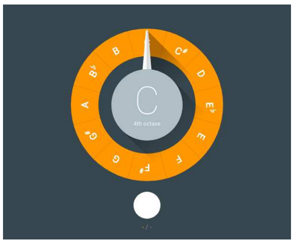


Figure 4.12: *Web based guitar tuner.*

- drum machine, it's a standard grid based rhythm maker that uses single-shot sound samples

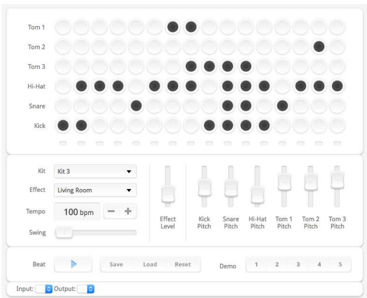


Figure 4.13: *Web based drum machine.*

- interactive loop-based music maker, it's similar to the drum machine concept but it uses loops instead of single-shot samples; the loops have shared qualities like bpm and scale so every random choice of loops sounds good

Figure 4.14: *Web based music maker.*

4.4.2 Development

In the web application I've developed, I needed something to create sound from scratch with the possibility to decide a type of sound and the possibility to change some of the sound's parameters in real-time.

Software synthesizer developed for the project The synthesizer developed for this project is based on a classic analog subtractive synthesizer, a Moog Minimoog is a perfect example of that. The analog signal routing system of this kind of synthesizer is represented in figure 4.15. The analog building blocks that constitute the synthesizer are some voltage-controlled oscillators (VCO), a low-frequency oscillator (LFO) used to modify some parameters, a voltage-controlled filter (VCF) controlled by an envelope (EG1, envelope generator) and a voltage-controlled amplifier (VCA) controlled by an ADSR envelope (EG2, envelope generator), The keyboard sends control voltage to the oscillator about the note that has been pressed, and also sends gate information to the envelopes to trigger the ADSR and the filter envelopes at every pressed note.

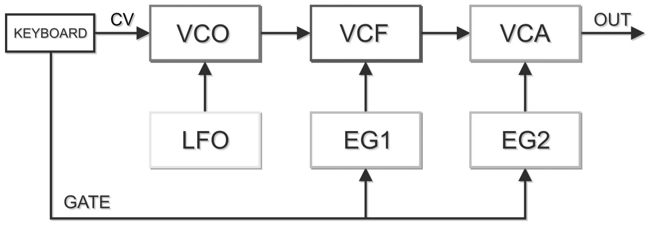


Figure 4.15: *Signal routing system of an analog subtractive synthesizer.*

The signal routing system for the implemented software synthesizer is a simplified version of the presented analog scheme. It is based on Web Audio API's objects that are the digital ideal versions of the analog components in figure 4.15 .

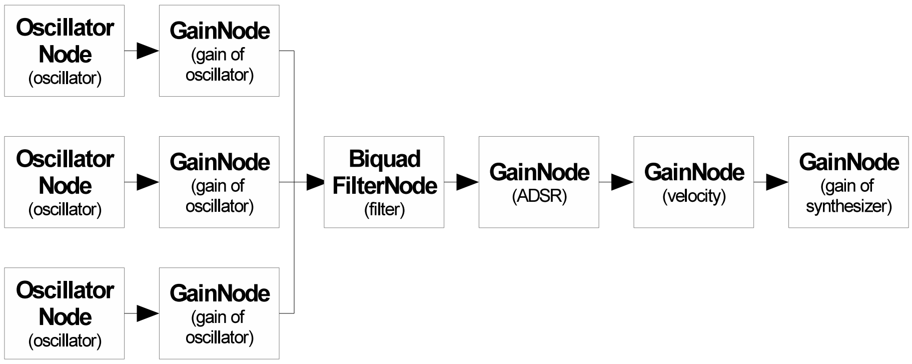


Figure 4.16: *Signal routing system of the implemented digital subtractive synthesizer.*

Before examining the signal routing system, let's describe the Web Audio API's objects used in the scheme: an OscillatorNode is a generator module that works as an oscillator with waveform and frequency as parameters, a BiquadFilterNode is a simple low-order filter object with an adjustable behavior between low-pass, high-pass and the other already mentioned common types, a GainNode is a processing module that change the volume of the input sound.

The synthesizer is composed of three oscillators[10] with adjustable gains, a filter with different possible behaviors, an ADSR envelope module, a velocity module[11] and a total synthesizer volume.

So to program a sound, the settable parameters in the composer panel are:

- generated waveform for every one of the three oscillators, possible values are sine, square, sawtooth and triangle
- gain for every single oscillator, possible values are in the range between 0 and 1
- transposition of the oscillator, possible values are in the range between -7 and 7; if the value is 0 the oscillator will play the scheduled note, if the

[10] Analog subtractive synthesizers like the Moog Minimoog and others from the same period had three standard oscillators with selectable waveforms and a noise oscillator.

[11] In the context of synthesizers controlled by a keyboard, velocity is the measure of how forcefully a key is pressed. This parameters makes it possible to play soft and loud notes giving dynamic to the performance.

value is -7 the oscillator will play the note an octave below, if the value is 7 the oscillator will play the note an octave above. This parameter is useful to create rich sounds; every value of the transposition keeps the oscillator to play only in the selected scale for the composition

- ADSR envelope, the values of attack, decay and release are defined in seconds and the slope of the functions that define this parameters can be set to linear or exponential; possible values for the sustain are between 0 and 1
- type of the filter, possible values are lowpass and bandpass
- cutoff frequency of the filter, possible values are between 0 and 22000 Hz
- Q of the filter, possible values are between 0.0001 and 1000
- total gain of the synthesizer, possible values are between 0 and 1

To compose a music that is slightly different at every session, the concepts of stochastic algorithmic music have been used. The procedures used to compose the music can be deterministic or stochastic. In the case of a deterministic procedure, given a specific input, the output is completely predictable because it depends on a fixed task. Stochastic procedures, instead, make use of random choices in the decision-making process, making the output more unpredictable.

The Musikalisches Wurfelspiel is an example of a stochastic way to compose music using a dice: several precomposed short musical pieces were used to create a whole musical piece, the number on the dice dictated the choice of the next precomposed piece to play. These types of games were quite popular also between the classical music composers, like W.A. Mozart, C. P. E. Bach and Maximilian Stadler, as a way to experiment new solutions. Simple stochastic algorithms used in compositions are the probability table lookup algorithms. They are based on a table of probabilities that indicates the likelihood of occurrence of the possible output values and a random number generator. The probability distribution is converted into a cumulative distribution and the randomly generated number is compared left to right with the cumulative distribution of the values to choose the output value. The following script shows an implementation example.

```
// param: choices, array of possible velocities
//        probabilities, array of probabilities
function randomVelocityWithProbabilities(choices,probabilities){
    var num=Math.random();
    var cdf = 0; //cumulative distribution function
    for (var t = 0; t < choices.length; t++){
        cdf =  cdf + probabilities[t];
        if(num < cdf) {
            return choices[t];
        }
    }
}
```

The probabilistic functions used in the project are based on the table lookup algorithm: one implies and uses uniform distribution of the possible values, while the other one accepts different probabilities for the output values. These functions are applied to the parameters that define a musical piece, like rhythm, notes and velocities.

Only notes of the selected musical scale are used and numbered from 0 to 56; the musical scale can be changed or selected randomly at every play to add a slight difference to the music. Three functions have been developed to program the note sequence: a random choice between a minimum and a maximum notes, a random choice between a list of notes with corresponding probabilities, a loop with a specific length of randomly chosen notes in a defined range. Also a way to specify the note sequence has been added to make it possible to program compositions with loops, i.e. repeating melodic lines.

The velocity of notes by definition are numbers between 0 and 127, they can be defined using three probabilistic functions to select random values between a minimum and a maximum values, to select random values from a list of possible velocities, to select random values from a list of possible velocities with corresponding probabilities. Another possible way is to define the velocities one by one.

The time signature is the standard 4/4, meaning that 4 beats are contained in every bar. The rhythm's notation is built on this notion using successive integer numbers to indicate the 16th notes of every bar[12]: 0 indicates the first 16th note of the bar, 15 indicates the last one. Rhythm is defined using the concepts of onset and duration of notes. The onsets of the notes can be chosen from a list of rhythms or can be randomly generated defining a loop length in bars and a number of notes. The notes durations are expressed as beats (1/4 of a bar), for example 0.5 indicates a note duration of half a beat (1/8 of a bar); they can be randomly chosen between some

[12]The motivation is explained in the "scheduling" section.

possible values optionally using specific probabilities. Onsets and durations can also be programmed in a non probabilistic way, to make it possible to compose a specific rhythm.

Scheduling When an audio application that uses the Web Audio API just needs to play a music composition, there is only one or two events to schedule: the play and stop of that composition. Since all the events are scheduled when the application is launched, this simple way of scheduling audio events is suitable for applications that play compositions that are already defined and don't have controls for parameters that change in real-time, for example a volume control. Instead, the developed application for the project uses real-time stochastic functions to compose the music and it also needs to be possible to stop the music whenever wanted and change the global tempo if needed. The mentioned simple scheduler doesn't offer this functionalities: instead of a single scheduling of all the events, the scheduling needs to be done in intervals. A timeout event and a scheduleAheadTime are used in real-time to divide the running time in intervals; the notes that will play in that interval are scheduled. An overlap between successive intervals is important to handle the possible delays of the clock for the timeout event without missing notes, and it is also important to find a suitable scheduleAheadTime value to avoid scheduling in the too far future: a large value will delay for example the stop of the music when the stop button is pressed.

Since relaxing music is slow and doesn't need extra short notes or complicated rhythms, the smallest note that can be scheduled in the application is a 16th note, meaning that the shortest note has a duration of 1/16 of a bar. So notes can begin at time instants multiples of the 16th note. For every interval, so every time the timeout event is raised, the scheduler checks all the valid time instants in that interval (time instants multiples of the 16th note between *current time* and *current time+scheduleAheadTime*) and schedules for every instrument the notes that have onsets in that interval.

Relaxing music is characterized by tempos that are usually around 45/60 bpm; the duration of 16th notes can be computed with the formula:

$$d_{16thnote} = (60/BPM)/4 \tag{4.1}$$

where 60 / BPM is the duration of a quarter note at tempo equal to BPM. To calculate suitable values for scheduleAheadTime and timeout time, let's consider the durations of short notes in seconds at various tempos.

	16th	8th	4th
40 bpm	0.375s	0.75s	1.5s
50 bpm	0.3s	0.6s	1.2s
60 bpm	0.25s	0.50s	1s
70 bpm	0.214s	0.428s	0.854s
80 bpm	0.187s	0.374s	0.748s
90 bpm	0.167s	0.334s	0.668s

Table 4.1: *Duration of notes in seconds at different tempos.*

Considering that the application at the same time receives packets from the EEG headset, create the music composition and manage the lights, it is necessary to take into account that the timeout event can present some delays. The timeout event can be called every 0.6 seconds with a scheduleAheadTime of 1 second, making sure there is overlap between successive intervals and the changes can occur soon enough.

Adaptivity As seen earlier, the real-time adaptivity of sound can occur by the modification of volume (total or of a specific instrument), spectrum/timbre (total or of a specific instrument) and tempo. The changes of the volume or timbre of a specific instrument are implemented modifying the gain or the filter of that synthesizer. The total volume and total spectrum changes are obtained by the connection of all the instruments to a low-pass filter and a volume modules. These modules are implemented in Web Audio API using a BiquadFilterNode and a GainNode objects, as done for the filter and gain modules of the synthesizer.

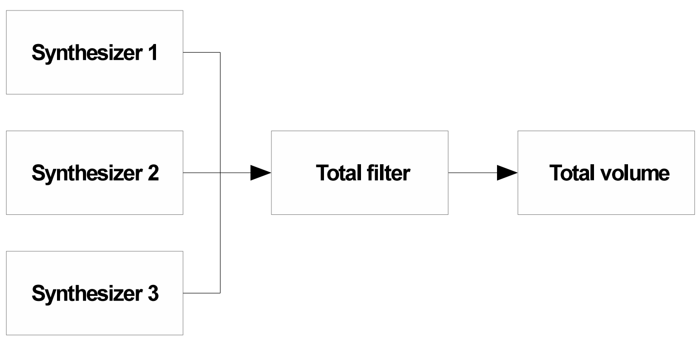
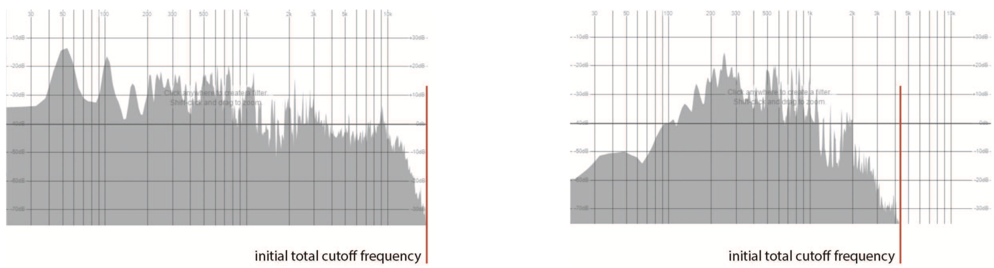


Figure 4.17: *Complete signal routing system.*

The initial settings of the *total volume* module are quite straightforward: since the object implements a simple change of volume, the initial settings represent full volume. Instead, the initial settings of the *total filter* module need some attention: if the synthesizers generate sounds with a strong presence of high frequencies, the *total filter*'s initial cutoff frequency can be set to full-open filter and the spectrum will change at every movement of the cutoff frequency during the adaptivity; but if the synthesizers use their low-pass or band-pass filters to generate sounds with less high frequencies, the *total filter*'s initial cutoff frequency needs to be automatically set to the highest frequencies present in that situation so the spectrum will change during the adaptivity. If the initial cutoff frequency in this situation was set to full-open filter, during the adaptivity the cutoff frequency would for the most part move without changing the spectrum because the high frequency portion of the spectrum was empty.



(a) (b)

Figure 4.18: *Position of the cutoff frequency in the case of present high frequency portion of the spectrum (a) and in case of no presence of high frequency portion of the spectrum (b).*

Because of the role during adaptivity explained in the "scenario" section, volume varies between 0 and the original value introducing and removing an instrument or the whole music, filter varies between 200Hz (only low frequencies pass) and full open, tempo modifications are limited between 0.75*tempo and the original value so the tempo doesn't become too slow.

Focusing on how the software is implemented, the sound adaptivity process works as follows:

- packets from the EEG headset arrive at every second
- these packets are forwarded to the sound tasks
- the tasks compute the new values for the parameters depending on the chosen adaptivity functions (linear, quadratic, mean) and on the selected effect (direct or inverse)

- the new values are applied to the parameters

The changes to the parameters are not instantaneous, the Web Audio API allows to apply changes using linear ramp functions so the changes are smooth, avoiding the not pleasant step-like effect.

4.5 Lights

4.5.1 Philips Hue

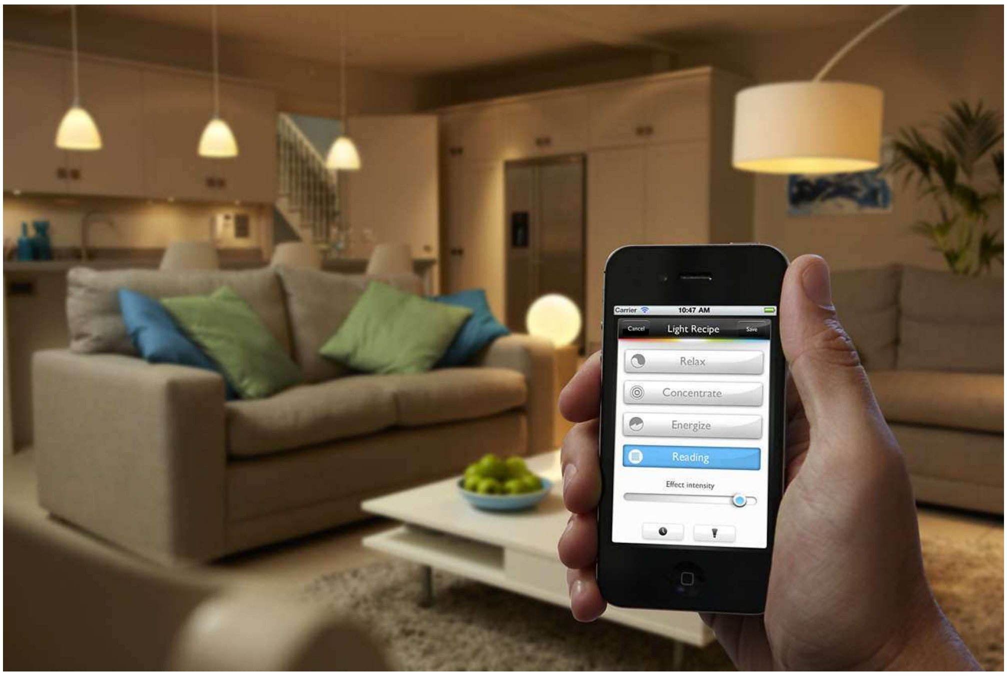


Figure 4.19: *Philips Hue.*

Philips Hue is a commercial wireless LED lighting system launched in 2012 (first generation) and updated over the years (second and third generation). It enables to have a customizable lighting in the house to create the right ambience for every activity and every room. The system is controlled via smartphones and tablets over Wi-Fi making its use intuitive and easy.

The lighting system is composed of bulbs, lamps and lightstrips; it's completely modular so the user can buy a basic kit and then expand it. Some physical controls are available as well, like motion sensors, dimmer switches and tap switches. The core of the system is the bridge that enables the communication between the app and the lights, and between the physical controls and the lights.

The application communicates with the bridge in the same network using HTTP calls. Every light has its own address, so these calls include the address of the resource to change, a method (get, put, post, delete) and a body that specifies how to modify the resource. The response message is in JSON format so it's easily read by the application. For example, to turn on a light the HTTP call needs to contain:

Address	http://<bridge ip address>/api/<username>/lights/<light number>/state
Body	"on": true
Method	PUT

And to change the color of a light to red the HTTP call should contain:

Address	http://<bridge ip address>/api/<username>/lights/<light number>/state
Body	"on":true, "sat":255, "bri":255,"hue":0
Method	PUT

These are just basic concepts, Philips Hue lights can be managed in advanced ways to handle schedules, scenes, events and sensors. Some libraries have beed developed to make it easier to code applications that use this lighting system using Javascript, C# and C++.

To understand the potentialities of Philips Hue, let's have a look at some 3rd party applications that use the system's potentialities in different ways:

- Sleep Cycle, it's an app that analyzes your sleep using the smartphone's microphone and wakes you up in the lightest sleep phase; it supports Philips Hue to simulate a natural sunrise

- Hue Thunder is a thunder simulation app that uses the lighting system to create an immersive experience; the settings recreate thunders in different scenes, for example on a rainy day or at the beach after a warm day and many others

- Huetro permits to set different light colors in different rooms using natural scenes as source for the color choice

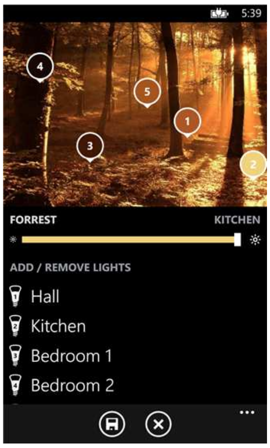


Figure 4.20: *Huetro app's color choice.*

- Ambify syncs lights with music using the microphone to capture the beat
- Sync My Lights creates a more immersive watching experience by synchronizing lights with the on-screen action of a movie

4.5.2 Synesthesia

Synesthesia is a phenomenon in which the stimulation of one sense causes an automatic involuntary experience in another sensory domain. The most common synesthetic perception is behind the way we categorize colors into warm and cool colors, using a synesthetic link between colors and thermal sensations. There are several types of synesthesia: for example people with grapheme-color synesthesia perceive characters as having specific colors, or people with auditory-tactile synesthesia feel like being touched in a certain part of the body when they hear a specific word. The type of synesthesia we are interested in is called chromesthesia, and it involves the association of sounds with colors.

Chromesthesia comprehends various kinds of sound-color associations. Some chromesthetic people can experience the association of one specific color to an entire musical entity like a whole song, a sequence of chords, a melodic line or an instrument; some others can experience the association of specific colors to single notes. Like every type of synesthesia, the personal synesthetic experiences of every individual are different, but there are some common aspects that are consistent or at least similar from one person to another. The brightness of the experienced color is the most consistent aspect between chromesthetic people, it usually depends on the volume, the spectral content and the pitch of a note (figure 4.21). A louder volume is associated with brighter colors, a lower volume is associated with darker colors. A timbre with a strong high frequency content is associated with brighter colors, a timbre with less high frequencies is associated with darker colors. High pitched notes are associated with brighter colors, low pitched notes are associated with darker colors.

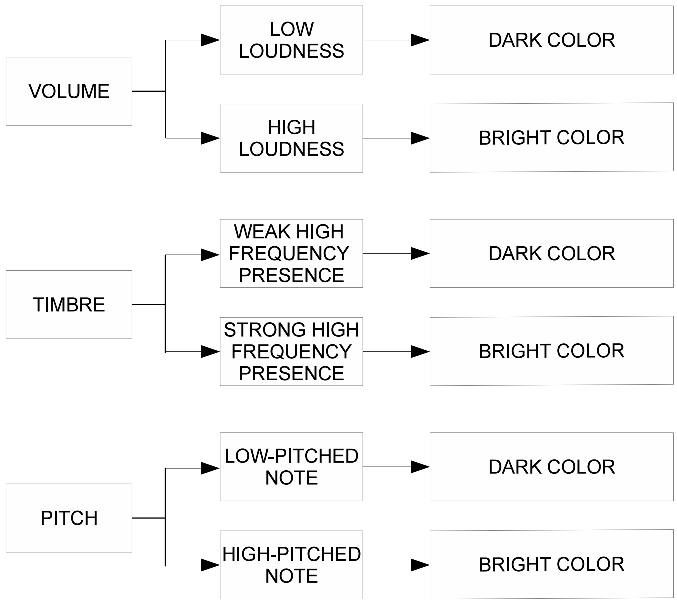


Figure 4.21: *Common synesthetic correlations between sound parameters and color.*

A less common chromesthetic experience has been widely studied by classical music composers, painters and researchers because of its potentialities: the association of colors and musical notes. Since the 18th century the development of color organs has been the incarnation of this concept making it possible to accompany music in a visual way using the pairing of colors and notes. The proposed mappings (figure 4.22) have some common aspects but they differ between each other proving that this aspect of chromesthesia is not entirely consistent between synesthetic people.

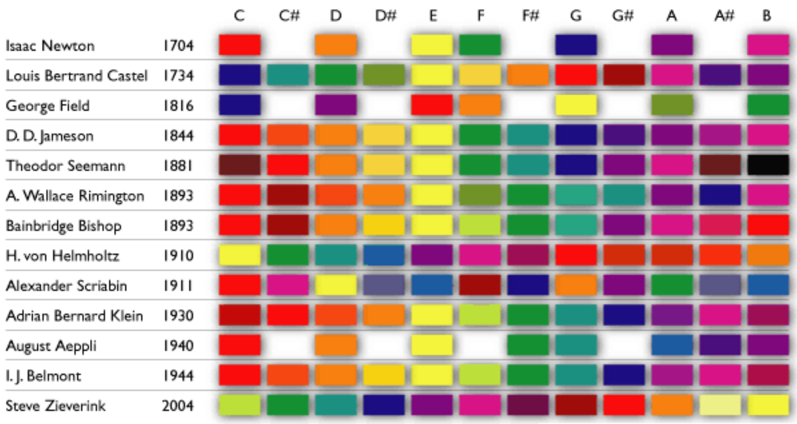


Figure 4.22: *Some studies on the correlation between colors and musical notes, picture taken from the website rhythmiclight.com*

4.5.3 Development

The concepts of chromesthesia explained in previous section are applied to create a connection between music and lights. A global color is set for all the lights; synesthetic perceptions of bright and dark colors associated with volume and timbre have been applied to vary the brightness, following how the sound is modified in real-time . All the lights of the system are controlled to behave in the same way to reach the immersivity of the experience. Since the Philips Hue system is modular and the lights are controlled globally, the developed software can be used with kits of different sizes. The suitable colors for this application are only the colors that can improve and help relaxation. To choose these colors it's necessary to underline the great difference between color applied on the walls for example for a calm environment and colored lights: when applied on walls, warm colors like red and orange make the environment more arousing compared to cool colours like green and blue that make it calmer and more relaxing[23, 50]; instead, when we talk about colored lights, warm colors are perceived as more cosy and less tense [7, 37]. Saturation is also an important aspect in lighting, heavy saturated colored lights are seen as more tense and less cosy with respect to lighter saturated colored lights [61, 60, 7]. So the colors suitable for this work are warm low-saturated colors like red, yellow, orange.

A library has been used in the project to program the lights: Node Hue API, a Javascript library that uses Node.js developed by Peter Murray. It enables to avoid the low level programming with useful functions to find the bridge in a network, connect to the bridge, control all the lights at the same time using the predefined global group 0 and set the group using different color standards like RGB, HSL, HSB and slow transitions.

Method	**Details**
turnOn()	Turn the lights on
turnOff()	Turn the lights off
brightness(percentage)	Set the brightness between 0-100
transition(milliseconds)	Specify a specific transition time
rgb([r, g, b])	Set a color as RGB value, integer numbers between 0-255
hsl(hue, sat, luminosity)	Set a color as HSL value, hue is a value 0-359, saturation is a percentage, luminosity is a percentage
hsb(hue, sat, brightness)	Set a color as HSB value, hue is a value 0-359, saturation is a percentage, brightness is a percentage

Table 4.2: *Some methods from the Node Hue API library.*

Adaptivity In the lights adaptation, the varying parameter is the brightness. This parameter can follow the global volume, the volume of a specific instrument, the global timbre or the timbre of a specific instrument. The adaptation of the brightness uses the already mentioned synesthetic concepts:

- a louder volume corresponds to a brighter light
- a softer volume corresponds to a less bright light
- a timbre with more high frequencies corresponds to a brighter light
- a timbre with less high frequencies corresponds to a less bright light

Focusing on how the software is implemented, a task controls the global light copying the settings of the sound adaptation of volume or timbre, computing the new value of brightness and applying the new value to all the lights in the system. As the implementation of sound adaptation, the brightness modifications are not instantaneous to avoid a distracting and non-relaxing step-like effect.

Chapter 5

Conclusions and future work

Starting from a previous work [14], in this thesis I have presented and developed a tool to automate a type of music therapy for children with neurodevelopmental disorders that involves listening to music in an adaptive relaxing environment created by suitable lighting. The goals of this technique are the relaxation of the patients and the training of their relaxation abilities; they are obtained through the adaptation of the audio and lighting environment to the child's state. An EEG headset is used to measure the relaxation level of the patient that represents the input of the software. After analyzing the scientific literature proving that relaxation can benefit children with neurodevelopmental disorders and proving also that relaxation can be induced through listening to music, four considerations have been reported as the foundations of this work:

- in the context of relaxation, listening to always different unknown music can have a greater effect
- changes of music tempo can enhance relaxation
- high sound frequencies tend to stimulate more with respect to low sound frequencies
- common connections between sound and color experienced by chromesthetic people are between louder volume and brighter colors, and between higher frequencies and brighter colors

These considerations lead to the implementation of an audio environment for the creation of stochastic algorithmic music and its always different reproduction using real-time scheduling of notes to make it possible to apply real-time modifications to sound parameters in response to the relaxation values of the patient depending on the goal of the session and how the adaptation is defined. Using the concepts of chromesthesia, lights follow these changes of the sound, keeping a connection between sound and colors to help create an immersive environment.

The settings permit to choose how the music and lights vary and how reactive they are: in a linear way, in a quadratic way or following the mean of the last values. So, depending on the goal of the session, reactiveness settings need to be chosen taking into account the stability of the relaxation level of the patient to avoid great sudden changes of music and lights: if the relaxation values are unstable and the reactive function is linear or quadratic, the environment will change producing non-relaxing results. Apart from this detail, the other settings could have been hidden behind three buttons, one for each goal. I made the choice of suggesting these three possible presets but keeping also open the full settings panel to let therapists experiment and, thanks to their experience, have the possibility to discover new potentialities of the software. As a matter of fact a possible third goal of this type of treatment was born trying all the possible adaptation settings, leading to the discovery of settings that can potentially be useful for training to handle more complicated sound stimuli.

The analysis tables collected during the sessions can be analyzed to understand how the child reacted to the session, and they can also be used to understand if this type of treatment with the same goal and settings could benefit also other patients in similar situations.

Testing will be an important phase to fine tune the settings with the collaboration of a composer experienced in the field of relaxing music and a therapist. Some tests have been performed with people not belonging to the target user group (for this motivation they have not been included here) to collect some first impressions regarding the relaxation enhancement scenario. Results seem encouraging, in particular the adaptation of the tempo seem to be an important feature to achieve deeper relaxation.

A fourth possible scenario could be investigated: using the same idea about the handle of various musical stimuli presented in the third scenario, those same settings can be inverted manipulating the music to make it simpler by lowering the volume and/or the high frequencies of one of the instruments to enhance relaxation when the child start feeling relaxed. This potential scenario seems to be possible if the music is tuned to the child to be relaxing but using the greater amount of music complexity he can easily handle.

To conclude, some possible future developments include the possibility to use musical instruments like piano or violin and, since this is a common aspect in relaxing music, sounds of nature. This can be achieved by implementing a sampler that can read single audio files and libraries of samples. Effect like reverb and delay can also be useful for relaxing music composition, as the use of more complicated stochastic functions that can achieve more musical results suitable for higher-functioning children. Tempo and frequency content variations have been used to enhance relaxation, a future work can look for other possible changes to reach the same goal.

Another possible behavior of the lights can be implemented using the correlations between colors and musical notes through a color-note mapping that uses only warm colors; the colors would follow an instrument playing long notes to avoid sudden changes that would produce a non-relaxing environment.

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