Final Project Report to the BIAL Foundation of the Project "Development and Testing of a Wearable Device for Neurofeedback of Physiological States"

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Summary

Objectives

The project focused on the development of a wearable, portable, but also a stationary device for neurofeedback of multiple physiological parameters in sound and light. This offers people to experience their weakly or non-perceptible physiological signals in real time with their outer senses of vision and audition. The aesthetic projection of light and sound allows them to tune themselves into a harmonic connection with their bodily processes. We aim on later therapeutic application that supports people to reconnect with themselves, e.g. in trauma therapy, depression, or dissociated states.

Developmental Phase

Two prototypes of a small, wearable feedback device have been developed that allow for real-time data processing, sonification and control of light sources. The first prototype is equipped with 2 analog-to-digital converters for direct read in of pulse and respiration data. EEG data can be received via a USB interface from the PC. A 32 bit microprocessor is used for data processing. Processed data are sent to a MIDI sound chip and to a light controller to drive the LED glasses. To be independent from a PC as EEG data source, we decided to develop and build a second prototype. It is equipped with a Bluetooth transceiver that can directly interface a small, wearable EEG amplifier measuring EEG, pulse or skin conductance simultaneously.

Several operation modes are possible with the technology that has been developed under this project. 1) The wearable system can either be controlled by a Brain-Computer Interface (BCI) which allows for feedback of complex signals or classified brain states. 2) The stand alone version of the wearable feedback device can directly read out a wireless connected wearable EEG amplifier. The feedback is given via three coloured LED glasses and headphones. 3) The software of the portable device has also been implemented in the PC-based BCI software for improved performance reasons. 4) Both, the PC and the portable version can control studio lighting systems and external speakers. In that mode, a whole feedback environment can be created that allows a person to experience the inner processes in the outer world. I have termed this feedback environment 'Sensorium'.

Experimental Phase

The hard- and software of the device have been tested successfully. In order to provide the best experience we started using the device in the full feedback environment setting. We built a computer-controlled lighting system and presented the sound with stereo speakers. Before testing this novel neurofeedback environment on subjects an appropriate questionnaire had to be developed that asks for personal experiences and allows for performance ratings of the device. This should give us hints for the usefulness of the device. In a pilot study, 20 participants have been exposed to their ongoing brain and heart signals while sitting inside the Sensorium, a small room equipped with a speaker and lighting system. We tested 10 experienced meditators and 10 non-meditators, both performing a meditative session of about 20 minutes. ECG (pulse), slow cortical potentials, and different EEG frequencies were fed back in real-time. A variety of different instruments was used.

Result and Conclusion

All participants were quite impressed and gave very positive feedback. Almost all of them reported an increase in contentment, relaxation, happiness, and inner harmony. They also reported of a widening of their body consciousness. In future, therapeutic paradigms will be developed and the treatment effects on people with psychological or psychosomatic diseases will be evaluated.

1. Introduction

Neurofeedback (NFB) is a method for training of self regulation of physiological, especially neurophysiological body signals. It became popular in the 70s already when the first devices for relaxation training were offered. The self regulation training was mediated by visual or acoustical real time display of, e.g., the muscular tension measured in the electromyogram (EMG) or the amplitude of the alpha rhythm activity of the electroencephalogram (EEG). The measurement implies electrode sensors to be attached to the brain or other body parts picking up the signals ranged from µV up to mV with frequencies between 0 and about 100 Hz. The EEG feedback era first started to become popular after Kamiya published his studies on operant conditioning of the EEG alpha rhythm. He found the alpha amplitude to be connected to the state of relaxation [1]. Since then, many biofeedback devices appeared on the market and often, these devices have been applied in non-scientific settings. Unfortunately, the hypothesis of a clear connection between EEG alpha power and relaxation could not maintain its position after further scientific explorations. The scientific investigations of brain physiological self regulation conducted by Sterman in 1974 described the application of EEG NFB for the therapy of patients with epilepsy [2]. Birbaumer and his group demonstrated the human ability for self regulation of the slow cortical potentials (SCPs), i.e. EEG potential shifts below 1 Hz [3], [4]. They also successfully applied the SCP feedback training to patients with intractable epilepsy for reduction of the seizure frequency [5], [6].

The major application of NFB currently is the treatment of attention deficit and hyperactivity disorders (ADHD) in children [7]. Kaiser and Othmer [8] did an extensive study including 1,089 patients with moderate pre-training deficits. In a NFB training of sensorimotor and beta waves a significant improvement in attentiveness and impulse control were found and positive changes as measured on the *test of variables of attention* (TOVA) could be demonstrated. Also Monastra et al. [9] who compared the effect of treatment with Ritalin and NFB in a sample of 100 children found similar improvements on the TOVA and ADD evaluation scale in both groups. Leins, Strehl et al. reported behavioral and cognitive improvements in children with ADHD after NFB-treatment. They compared the feedback training of beta/theta power with feedback of slow cortical potentials (SCP) in two groups of 19 children (aged 8-13 years) each. Both groups learned to regulate their EEG parameters and showed significant behavioural, attentional, and cognitive improvements which remained stable in a follow-up measurement six months after treatment [10], [11].

Other studies using NFB of Theta band activity successfully showed increases in intelligence scores and academic performance [12]. Egner and Gruzelier found an improvement in musical performance by alpha/theta NFB training in which the participants should try to raise the theta power over alpha [13]. Further applications of NFB can be found in the treatment of learning disabilities, conduct disorder, cognitive impairment, migraines, chronic pain, sleep dysregulation, autism-spectrum-disorders, post-traumatic stress disorder and mild traumatic brain injury, etc..

NFB also was used in Brain-Computer Interfaces (BCIs) for the training of direct brain-computer communication and peripheral control via self-regulation of brain signals. In contrast to a normal NFB device, a BCI is able to classify a brain response into classes with intentional meaning. This is often accomplished with certain kinds of discriminant analysis. For example, users learned to regulate their slow potentials so the computer could distinguish between a positivity or negativity response [14], [15]. Others learned to regulate their mu-rhythm activity by imagination of a hand movement which could be detected by a classification algorithm [16]. Further, a BCI is able to convert the intentional brain responses into action, e.g. letter selection for verbal communication, controlling switches or prostheses. The Thought Translation Device (TTD) used for realizing the here described Sensorium is both, a NFB device for feedback training of slow cortical potentials but also oscillatory components and a BCI that allowed completely paralyzed patients to communicate verbally using the self regulation skills of their brain signals [17].

The advances in the field of BCI research demonstrate that it truly is possible to self regulate certain brain parameters voluntarily with a high reliability. However, this research also demonstrates that not every signal component is suitable for self regulation and for some components such as the slow waves it is highly individual whether a person can learn voluntary regulation. The amount of alpha and sensorimotor rhythms also has been shown to be highly individual. And while for the NFB treatment mostly the theta, alpha or beta waves of unspecific areas were trained, for BCI control these components were not of interest at all. Here, it is consensus that motor-related rhythms such as the mu-rhythm over motor areas are the best controllable components while the alpha rhythm can hardly be used as it is closely connected to visual processing, and theta rhythms are connected to drowsiness or very special states of consciousness such as hypnagogic states or some specific styles of meditation.

Looking at the outcome of various NFB studies one can realize that there is often a rather poor learning effect in the neurophysiological self regulation training however the treatment effect often shows quite impressive results with effect sizes around 0.4-0.6 [18], [19]. This might be the reason why some researchers even don’t report the neurobehavioral data but only the psychological behavioural treatment outcome. Beside the research considering NFB as an effective therapy for various different diseases, other researchers like Loo & Barkley doubt that changing the EEG is the actual mechanism for the decrease of symptoms [20]. Therefore, it could be caused by a placebo effect and rather be an unspecific treatment effect.

This would suggest that the effectiveness could be far more assigned to the feedback itself and the setting as such than to the self regulation skill of the patient. As a consequence, NFB as such or as an intervention method can be regarded to be suitable for positively changing psychological variables; however, the true mechanisms still remain unclear. This asks for a plausible explanation. Here is one attempt or hypothesis. The specificity of NFB therapy in contrast to other forms of medical or behavioural treatments is that NFB very closely connects the patients' consciousness with their physiology. This might improve their body awareness as well as the connection between self and body. As a consequence, the patient may become more aware of the relation between body and consciousness and thus create a stronger link between both which facilitates behavioural changes as necessary for improving ADHD symptoms for example.

This consideration may serve as a basic mechanism for the success of the Sensorium as a form of a NFB intervention that optimizes the feedback experience as such without the requirement of performing self-regulation training. The Sensorium can be regarded as a whole NFB environment placing an emphasis on an enhanced sensation and extraordinary self-experience of the patient during a session.

I. Developmental Phase

2. Hardware Development

Two prototypes of an electronic feedback device have been developed and built. We have called these devices MediTrain. All electronic circuits were realized in SMD technology for obtaining small built sizes. The MediTrain device is a small, wearable device that allows for real-time data processing, sonification and control of light sources. The following schematic shows the basic idea of the functionality and the components which could be attached to the MediTrain device. The actual realization of this idea is presented in the following paragraphs.

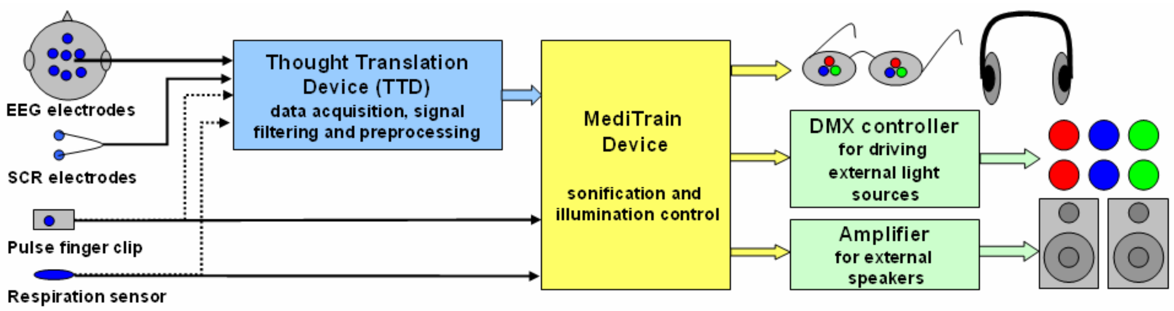


Figure 1. Basic idea and general overview of the multisensory and multimedial feedback system. The TTD is installed on a PC and is used for data acquisition and preprocessing of the EEG and peripheral signals. It is also capable of brain state classification. The wearable MediTrain device performs the sonification and illumination control of all physiological input signals. It can drive the headphones and 3-colored LED glasses. For driving an external feedback environment MediTrain can be connected to a stereo amplifier and a DMX light control unit.

2.1 The First Prototype MediTrain 1

The following picture shows and explains the first prototype of the MediTrain device. The prototype was equipped with two 24-bit analogue-to-digital converters for direct read in of the pulse and respiration data. The devices for the acquisition of physiological data as well as the USB interface were optically decoupled from the device for safety reasons. Additionally, EEG data from the PC could be received for further processing via a USB interface. A 32 bit microprocessor (Atmel AT32UC) was used for data processing. A second 8-bit processor was required for control of the menu and display. Processed data were sent to a MIDI sound chip and to a light controller that can drive coloured LEDs.

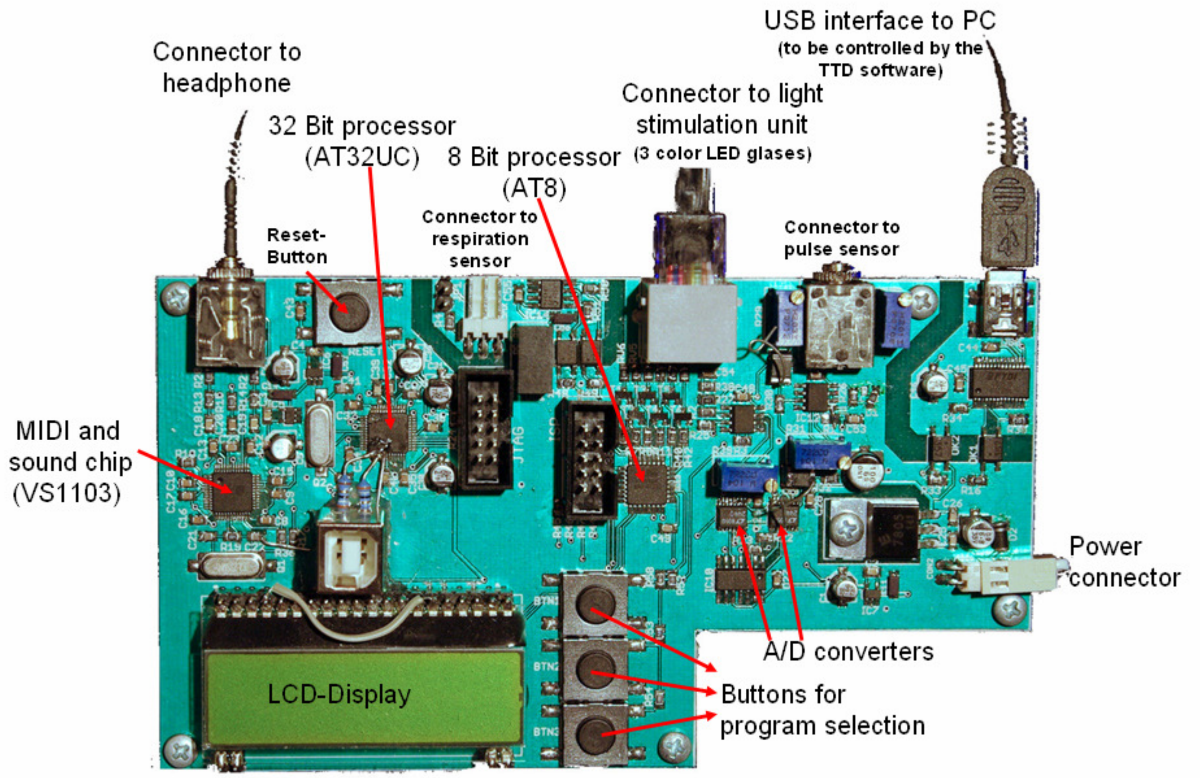


Figure 2. Functioning prototype of the MediTrain 1 hardware.

This prototype led us to a huge learning process in the hardware development for such specific applications. The two sided circuit layout was designed with CAD editor software. The software was developed on the PC and transferred to the processors via a specific USB flashing interface. However, with this first device it was not possible to read in EEG data directly without using a PC with the Thought Translation Device Software. As we wanted to be as independent as possible from the use of a PC, we decided to develop and build a second prototype because a modification of prototype 1 to reach this aim was not possible.

2.2 The Second Prototype MediTrain 2

The second prototype was equipped with a Bluetooth transceiver that can directly interface a small, portable EEG amplifier. When interfacing the Nexus 10 device or the Brainquiry PET device, one can measure EEG and pulse or respiration or skin conductance simultaneously. For this reason we decided to skip the A/D converters in this version. Initially, a PET device interface was programmed. Additionally, an output for connecting a DMX control unit for light control was added as well as an SD-card reader for storage of data and program parameters. The following figures show the block diagram and an explained photograph of prototype 2 of the MediTrain device. One A/D converter can be optionally added to allow for measurement of respiration or temperature. Again, for safety reasons, the USB interface and the DMX out interface were optically decoupled from the rest of the device.

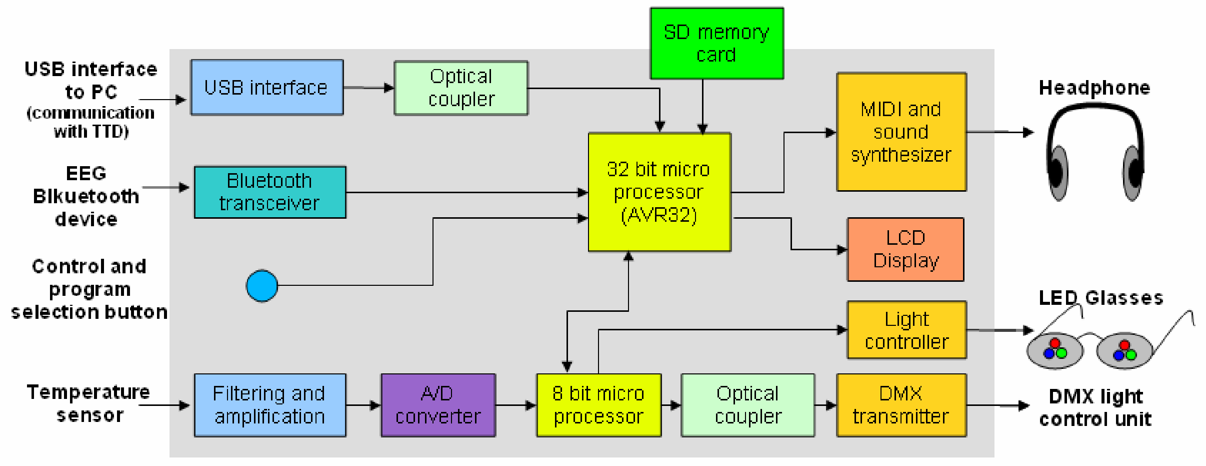


Figure 3. Block diagram of the hardware components of prototype 2 of the MediTrain device

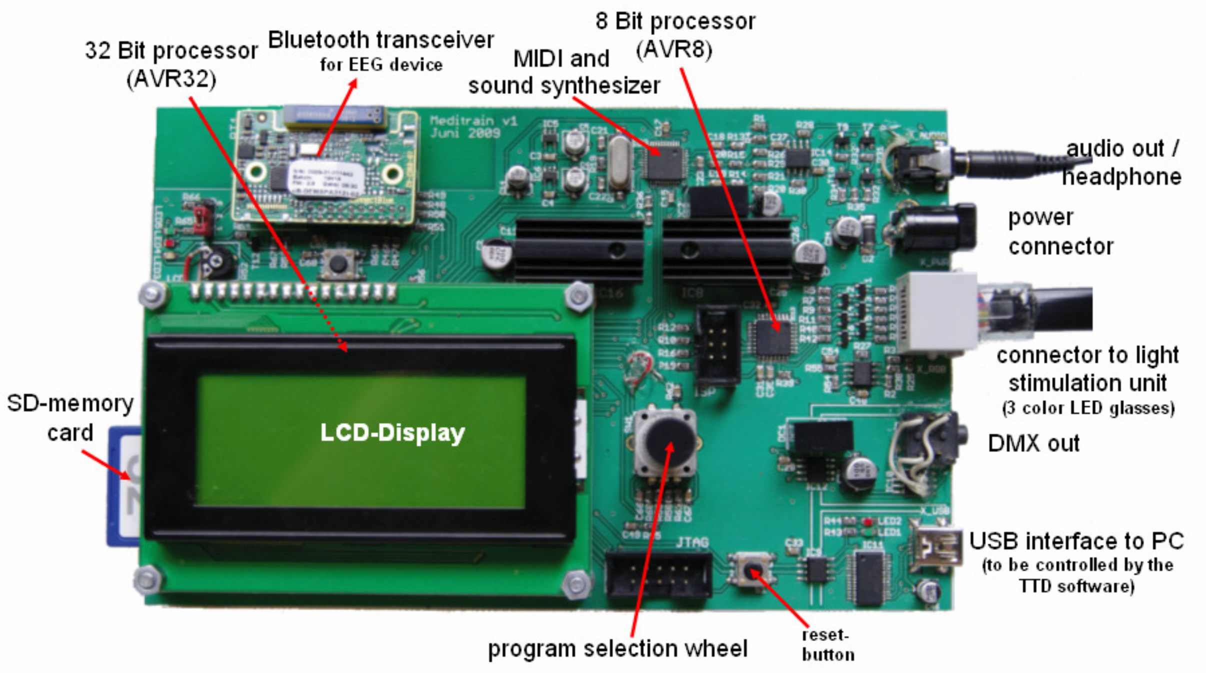


Figure 4 shows the manufactured prototype 2 with the explanation for the most essential parts.

The whole device can be controlled with one selection wheel. The menu structure can be followed in this table:

Table 1. By turning the selection wheel and pressing the wheel one can select an item and change the level. Menu level 2 holds the submenus of level 1.

Menu Level 1	**Menu Level 2**	**Remark**
Select Vibe	List of Vibe program names	various Vibes can be selected
Set Instrument	Midi ID …	the instrument of each Midi ID in the current vibe can be changed
Mode	USB	Data will be received from USB interface
	Bluetooth	Data will be received from Bluetooth interface
	Direct in	Data will be received from optional A/D converter
mScale	0.1 to 10	Master scaling factor can be changed in the range between 0.1 and 10

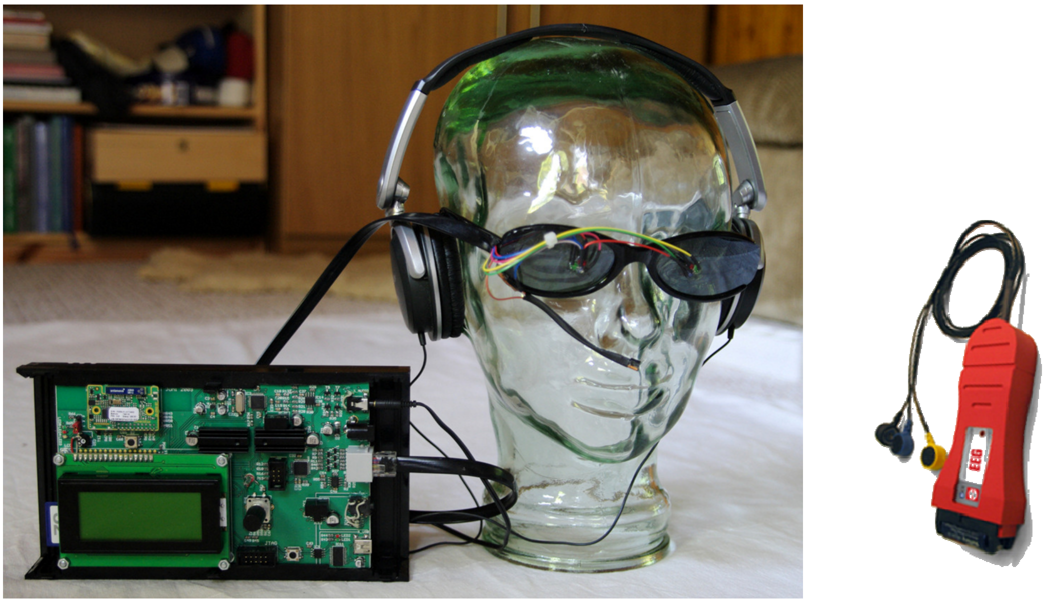


Figure 5. The complete stimulation unit consists of the MediTrain device (version 2) plus headphones and 3 colour LED glasses. This device can receive data from the PC (Thought Translation Device Software) or directly from a portable EEG amplifier such as the PET device as shown on the right.

3. Software Design

Three different software packages were developed:

1. A firmware for the MediTrain device that provides a framework for hosting the real-time signal processing and sonification modules and also offers a user interface for program selection, control of the built-in display and control of the interfaces (USB, Bluetooth, SD storage chip, light and midi controllers). All software was programmed in C or C++. For transferring data and setup parameters to and from the TTD a communication protocol was defined. Additionally, a protocol for data transfer within the TTD software for interfacing the MediTrain device was defined and programmed. Thus, the TTD software is able to configure the MediTrain device via USB connection

and also send data streams, either directly from an EEG amplifier or from a pre-recorded file to the device. The TTD can be used to preprocess EEG data.

2. A major workload was the re-programming of the whole sonification software POSER. The new system and algorithm was called SymPOSER. It includes the modified sonification algorithm plus a system for parameterized light control. The software was programmed in portable C++ classes which can be used either directly in the TTD for sonification and light control or in the MediTrain device for sonification and light control. This should give the MediTrain Device the same capabilities as the PC version.
3. For using the PC as a comfortable sonification device, the SymPOSER module was implemented in the TTD software. Here, a user-friendly graphical setup and sound configuration tool had to be programmed. The sound configurations, which have been created with the TTD can then be used in the MediTrain device as well.

3.1 The MediTrain-Software

The software of the MediTrain device is structured according to Figure 7. The central unit that instantiates and controls most other components is the ControlUnit. It holds the Graphical User Interface GUI handling the display and selection of the operation modes and programs. The ControlUnit also controls the USB_Interface for connection with a PC that runs the TTD-software, and the EEG control unit PETDevice that collects the data via the Bluetooth interface. The POSERFrame is the core unit of the sonification and illumination control that is also held by the ControlUnit and fed with the acquired signals. The FOSERFrame instantiates a number of POSER_Filter classes, one for each filter component, such as the theta or alpha rhythm. Each filter output can be used as input for a POSER_MIDI instance which sonifies the signal. It also can be used for light control which is processed in an instance of the POSER_Light class. This will be explained in greater detail in the next paragraph and shown in Figure 8. The parameters of an entire sound and light setting are stored in the container classes POSER_Vibe and POSER_Params. A vibe is defined by a set of filters, MIDI, and light instances. The user can select a variety of predefined vibes with the selection wheel on the device. This is controlled by the Vibehandler unit.

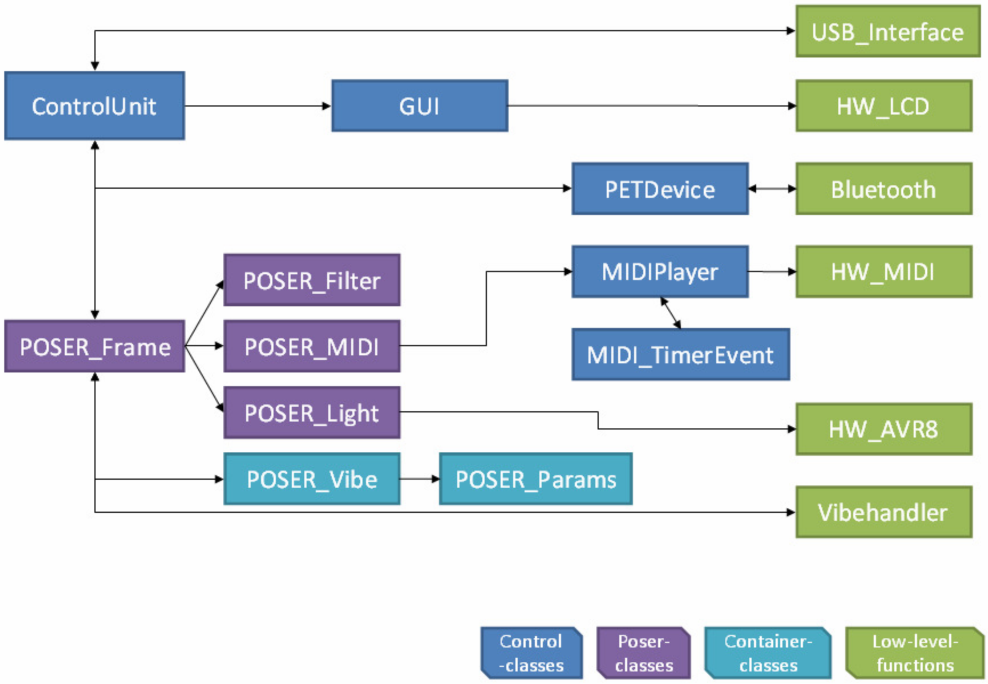


Figure 6. Softwaredesign of the portable MediTrain Device. Each component is a C++ class which might have more than one instance.

3.2 The New SymPOSER Sonification and Illumination Algorithm

For the development of the Sensorium, the POSER sonification software module was completely re-programmed. The new system and algorithm was called SymPOSER. It includes a modified sonification algorithm plus a system for parameterized light control. Parts of the software were programmed in portable C++ classes so they can be used either directly in the TTD or in external hardware devices for sonification and light control which we also have available. Additionally, for the TTD a comfortable setup and sound configuration tool was programmed. In the following, a short description of the functional elements of the software is given.

SymPOSER consists of three basic processing classes, a filter class, a Midi control class, i.e. the sonification class, and a light control class. A central parameter container class holds all filter, Midi, and light control parameters. The filter class contains two selectable types of signal filters, an FIR (Finite Impulse Response) band pass filter and an IIR (Infinite Impulse Response) filter that can either be configured as band pass, or high or low pass filter. Such filters can be used for separation of the typical EEG frequency bands but also for the isolation or extraction of meaningful components within an ECG or other physiological signals. The filtered data stream can either be directly used as output signal, or be subject to further processing such as the calculation of the band power, the identification of wave extremes which later can be used for triggering the touch of a note, and the conversion of the time between two maxima into a frequency output. This provides four different output signals of a filter class. For each frequency band or signal component a separate instance of the filter class is created as shown in Figure 7. The second base class, the Midi class is the sonification unit which transforms the signals provided by the filter class into Midi commands and sends them to the Midi device. Four different parameters of a Midi note can be modulated by any of the

filter output signals. These are note, touch velocity, pitch, and amplitude. With pitch and amplitude modulation, a continuously played tone can alter its frequency or loudness resulting in a vibrato or frequency modulation in accordance to a brain signal. A common sonification setting uses the wave trigger output to initiate a sound that is played with the pitch (note modulation) of the frequency output and the velocity according to the amplitude of the wave cycle. The note modulation can be tuned to 12 tone music, major, minor or pentatonic harmony. Each Midi instance is able to play one instrument which can be selected out of 127 instruments according to the Midi wavetable to which the system is linked. Similarly to the Midi class, a number of light control instances transform the signal into light values sent to a DMX interface that controlling a light system. The DMX standard is a serial interface standard used in professional studio and theatre lighting systems. Any output signal from the filter instances can be used to modulate multi-coloured lighting devices.
For setting up the parameters a visual interface was programmed that allows to overview and change the parameters of all instances. Another program tool was created that provides the option for managing pre-set parameters and a further tool contains a sequencer for running various sonification settings in a sequence. This was used in the Sensorium study to present a fixed sequence of varying sonifications during a session in a standardized manner for each participant. Figure 7 gives an overview of the SymPOSER components as a module of the TTD.

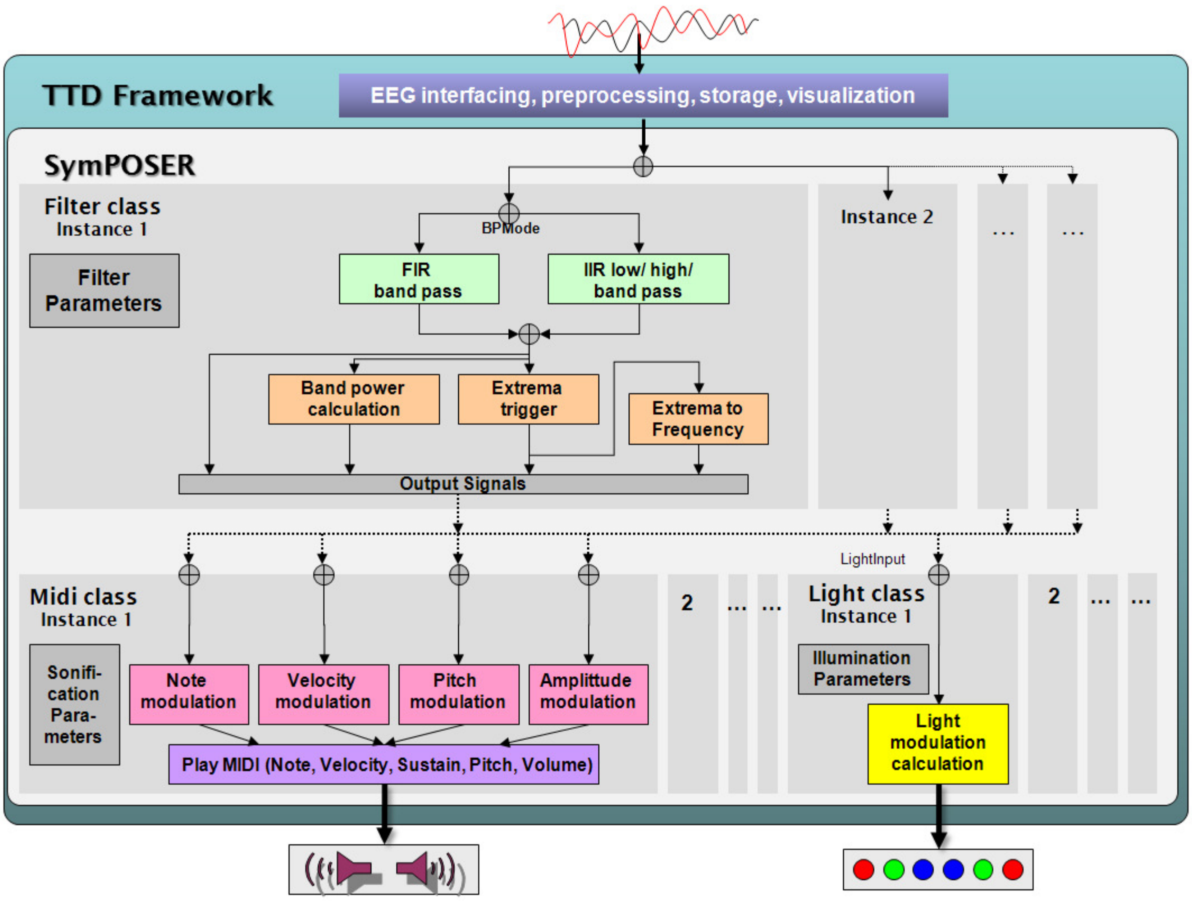


Figure 7. Block diagram and structure of the SymPOSER module. The SymPOSER framework contains instances of the three classes, a filter class, a Midi class for sonification, and a light control class. Each instance of the filter class provides the filtered signals for sonification or light control. Each Midi instance can sonify one EEG component that is played by a specific instrument.

3.3 The TTD Implementation

Basically, a PC or Notebook PC is required for running the TTD software. The TTD is capable to interface about ten different types of EEG and physiological amplifier systems. When connecting the Nexus 10 amplifier device or the Brainquiry PET device, one can measure and present EEG and pulse, respiration and skin conductance simultaneously. Those two devices are portable and transmit the signals wireless via Bluetooth to the computer. The TTD performs the signal processing and conversion into sound and light using the above described SymPOSER algorithms. The use of the TTD brings three major advantages. The first is the comfortable graphic user interface for dynamically creating and changing vibes. The second advantage is in the possibility of obtaining a high audio quality by using external software sampler, and third, an additional sequencer component allows for automatized changing of vibes with cross fading so that a sequence of different vibes can be presented during a session in a standardized manner. The editing of a vibe is shown in figure 8. The filter, MIDI, and light instances of a vibe can be edited in separate tab sheets. Figure 8 shows the tab sheet for the filter editing. In the editable table there are all filter parameters listed for each of the 13 different filter instances active at the moment. The graph at the bottom of the page shows the various filter output signals. The same editing and visualization structure is available for the sonification and lighting settings (see Figure 9 for the sonification).

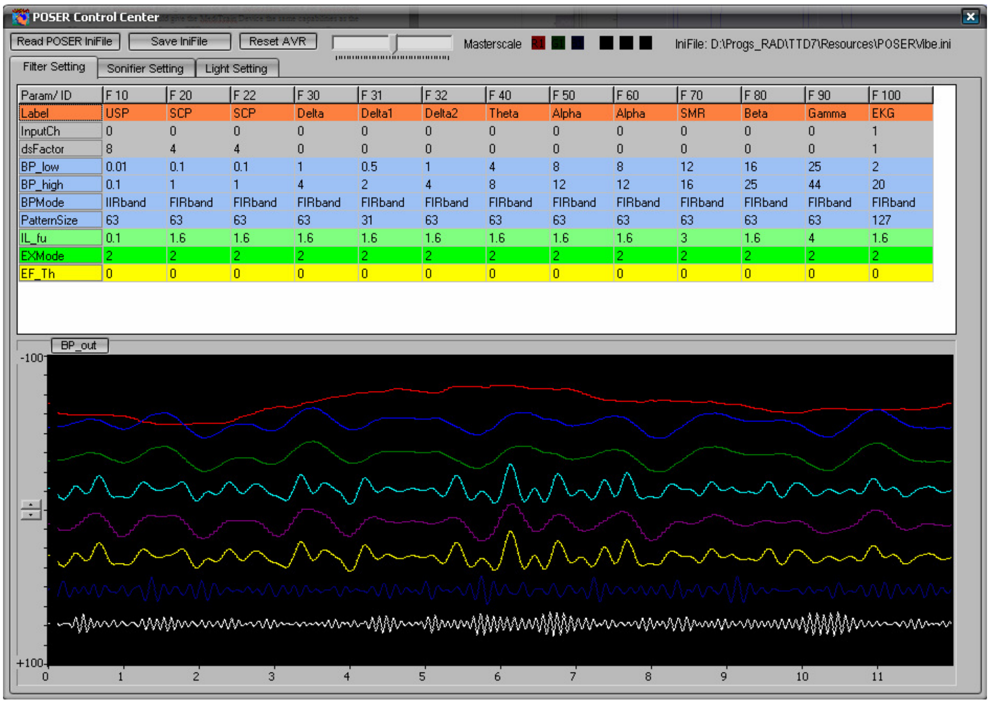
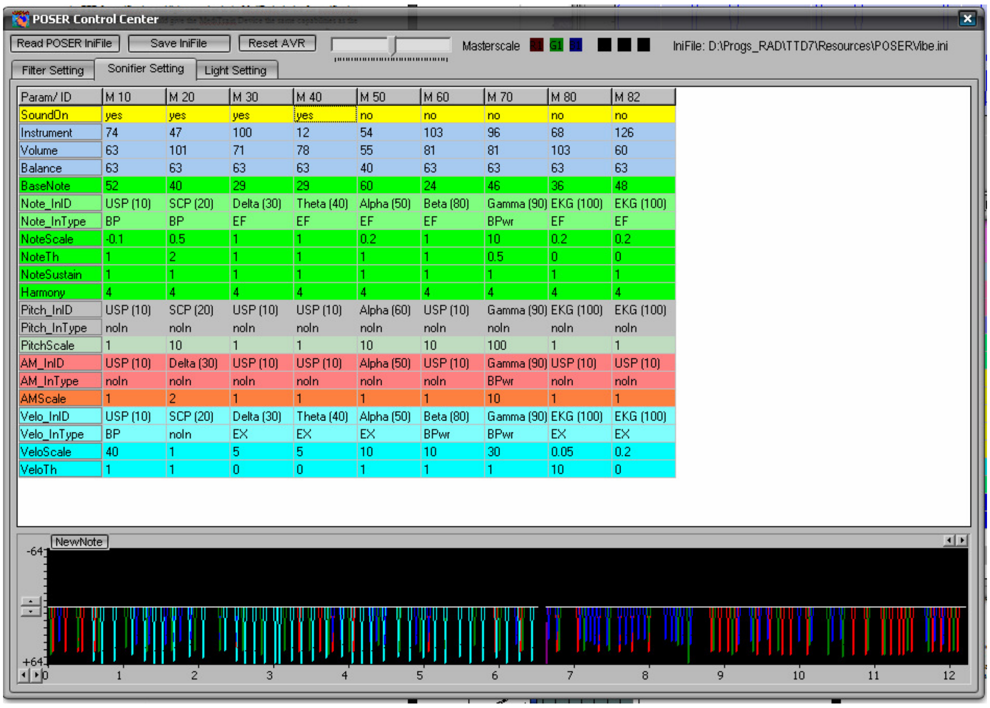


Figure 8. The filter parameters for each instance are listed in the upper table while the filtered signals can be viewed in the window below.



Param/ ID	M 10	M 20	M 30	M 40	M 50	M 60	M 70	M 80	M 82
SoundOn	yes	yes	yes	yes	no	no	no	no	no
Instrument	74	47	100	12	54	103	96	68	126
Volume	63	101	71	78	55	81	81	103	60
Balance	63	63	63	63	40	63	63	63	63
BaseNote	52	40	29	29	60	24	46	36	48
Note_InID	USP (10)	SCP (20)	Delta (30)	Theta (40)	Alpha (50)	Beta (80)	Gamma (90)	EKG (100)	EKG (100)
Note_InType	BP	BP	EF	EF	EF	EF	BPwr	EF	EF
NoteScale	-0.1	0.5	1	1	0.2	1	10	0.2	0.2
NoteTh	1	2	1	1	1	1	0.5	0	0
NoteSustain	1	1	1	1	1	1	1	1	1
Harmony	4	4	4	4	4	4	4	4	4
Pitch_InID	USP (10)	SCP (20)	USP (10)	USP (10)	Alpha (60)	USP (10)	Gamma (90)	EKG (100)	EKG (100)
Pitch_InType	noIn	noIn	noIn	noIn	noIn	noIn	noIn	noIn	noIn
PitchScale	1	10	1	1	10	10	100	1	1
AM_InID	USP (10)	Delta (30)	USP (10)	USP (10)	Alpha (50)	USP (10)	Gamma (90)	USP (10)	USP (10)
AM_InType	noIn	noIn	noIn	noIn	noIn	noIn	BPwr	noIn	noIn
AMScale	1	2	1	1	1	1	10	1	1
Velo_InID	USP (10)	SCP (20)	Delta (30)	Theta (40)	Alpha (50)	Beta (80)	Gamma (90)	EKG (100)	EKG (100)
Velo_InType	BP	noIn	EX	EX	EX	BPwr	BPwr	EX	EX
VeloScale	40	1	5	5	10	10	30	0.05	0.2
VeloTh	1	1	0	0	1	1	1	10	0

Figure 9. All sonification parameters can also be viewed and changed in a table for each sonification instance separately.

4. The operation modes of the feedback environment

4.1 The MediTrain-TTD Feedback Device

This is the initial version of the device which we proposed at the beginning of the project. The physiological data are captured with an EEG device connected to a computer that runs the TTD neurofeedback software. The TTD is used for data acquisition, storage, and preprosessing of the signal. The wearable MediTrain device retrieves the signal via USB and performs the sonification and visualization of the data. The user is exposed to this stimulation by headphones and colored LED glasses. This operation mode is available in prototype 1 and 2.

4.2 The Standalone MediTrain Device

This final version of prototype 2 does not require any external computer anymore. A small, portable EEG amplifier (PET device) is interfaced to the MediTrain device via Bluetooth wireless technology. The MediTrain software does all signal processing and filtering and also the sonification and light control. The fully wearable system allows for movement interaction with the sonified physiological signals.

4.3 The Feedback Environment “Sensorium”

The Sensorium is a feedback environment that resulted from the developments and provides the highest quality of feedback. The EEG-device is still portable and transmits the signals via Bluetooth to a notebook PC that runs the TTD software. The TTD performs the signal processing and conversion into sound and light using the above described SymPOSER algorithms. Additional sampler software can be used to convert the MIDI commands generated by the SymPOSER into high quality sound that can be presented with a good sounding stereo amplifier and loudspeaker system. The light stimuli are sent to a DMX interface that is able to drive any studio light system. We have built two types of lighting for the Sensorium. The first are colored spot lights which are best for indirect illumination of blank walls or curtains. The second is a white semitransparent ball that is enlightened by colored super bright LEDs. The Sensorium offers the user a high degree of freedom to either sit or move in the room, similar to the other MediTrain solutions. However, it requires a whole installation in the room and therefore is less suitable for a spontaneous use in home environments. Compared to the MediTrain devices the feedback experience is different. While the MediTrain device provides feedback through glasses and headphones and thereby shields the users space of consciousness from the outside world, i.e., the user is brought more into a state of introspection, the Sensorium projects the signals from within the body into the outside world leading to a more widening experience. The complete signal diagram is illustrated in Figure 10.

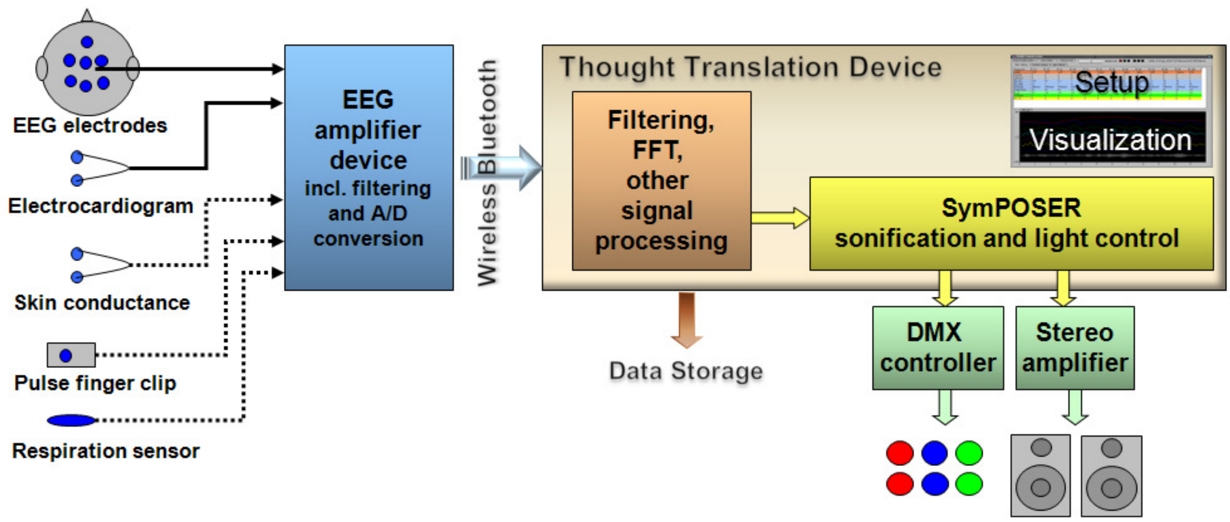


Figure 10. General overview of the multisensory and multimedial feedback system 'Sensorium'. The TTD software is installed on a PC and is used for data acquisition and pre-processing of the EEG and peripheral signals such as the Electrocardiogram (ECG), skin conductance, or respiration. It is also capable of on-line brain state classification. The SymPOSER module transforms the signals into sound and light. For driving an external feedback environment the sound should be presented over a stereo speaker system and the light control signal is sent to a DMX control unit for driving any studio lighting system.

4.4 Comparison between the Operation Modes

The following table summarizes the features of the three different operation modes which resulted from our developments.

Table 2. Comparison between the feedback devices and operation modes.

Feature	MediTrain - TTD	MediTrain Standalone	TTD - Sensorium
Hardware requirements	EEG amplifier PC or notebook MediTrain device LED-glasses Headphones	PET EEG device MediTrain device LED-glasses Headphones	EEG amplifier PC or notebook Audio amplifier and loudspeakers DMX interface Light system
Software requirements	TTD with SymPOSER module	none (TTD only for configuration)	TTD with SymPOSER module
Wearability	+ EEG and MediTrain are wearable - USB connection to PC required	+ EEG and MediTrain are wearable + no external wires when battery driven	+ EEG is sole device to wear + independent from headphones and glasses - requires installation in a room
Sound	MIDI chip with fixed samples - Moderate sound quality	MIDI chip with fixed samples - Moderate sound quality	+ Additional sampler software can be used + high quality
Light	LED - glasses	LED - glasses	Spot lights, Light ball Any studio lighting system

II. Experimental Phase

5. Initial Pilot Study in a Novel Feedback Environment

5.1 Experimental Setting

Before testing the sound and light neurofeedback on subjects a questionnaire had to be developed. This questionnaire is finished and asks for the personal experiences and allows for performance ratings of the device.

5.1.1 The Hardware

Due to the high quality of sound and also the spacious lighting possibilities we decided to do the pilot study within the Sensorium.

Figure 11. Participants sitting inside the Sensorium watching and listening to their own physiological signals. The technology and the experimenter were placed to the remote periphery.

5.1.2 The Stimulus Design

The selection of sound and light stimuli in such kind of experiments is both, an aesthetical and a scientific question. For obtaining high quality sounds the internal sound card was not appropriate. Therefore, the MIDI commands generated by the SymPOSER module were sent to an additional software sampler program offering an improved sound quality.

The beginning and final phase of the session was occupied with the basic sound of the heartbeat. The ECG was sonified with two instruments, a smooth deep bass, played at each R-peak and the ECG Padmix, i.e. a drone sound with water drop like tingles played with the R, P and T peaks of the ECG. After the initial first minute of ECG, a smooth flute sound started playing the amplitude changes of the ultra-slow potential changes (USP) between 0.01 and 0.2 Hz. In addition, the delta frequencies between 1 and 4 Hz were added with strings. During the time between 5:15 min and 8:00 min the 4-8 Hz theta waves were played with a vibraphone. In the middle of the session, the slow cortical potentials between 0.01 and 1 Hz were played by harp sounds. In this setting, we preferably intended to use preferably slow EEG components which were supposed to calm down the organism and more easily allow tuning into the signal variations and rhythms. Also, it seemed to be more supportive when avoiding fast changes in the lights and flashes. Therefore, the USP were coded into a blue-red contrast. Positive slow potential shifts as generated on the cortex in relaxing moments should lead to a blue coloured environment while negative shifts normally reflect attentive moments in which the brain produces a readiness state (i.e. the 'Bereitschaftspotenzial') which turned the environment into red. This archetypical association between colour and state could result in an intensification of a certain state (which was not proven here). The smoothed band power of the alpha rhythm was used to modulate the brightness of a green spotlight that super-positioned the other lights. In the first sessions, a yellow peripheral spotlight was modulated with the heartbeat. As this appeared to be distractive for some people, why this yellow spotlight was no longer used in the later sessions. Figure 12 illustrates the sound and light sequencing.

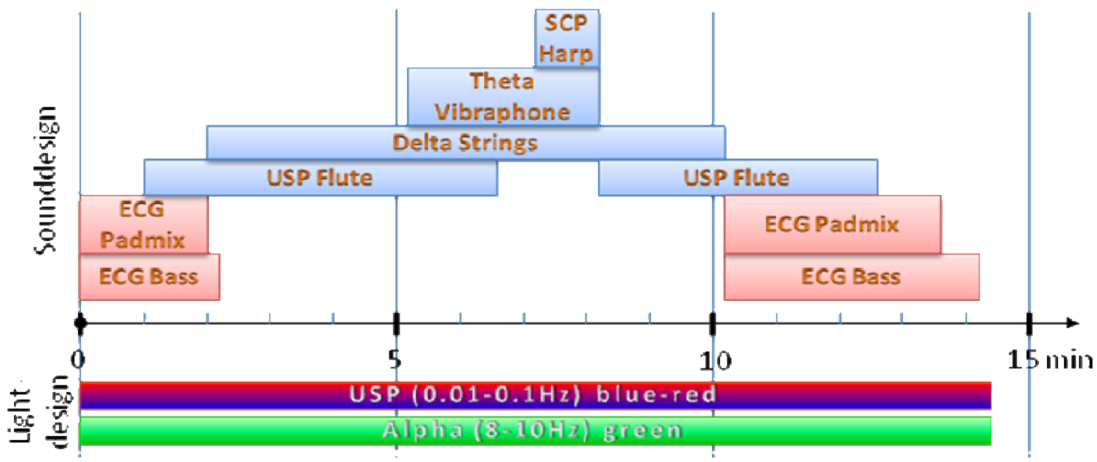


Figure 12. The sound and light design is depicted in a time flow graph. Inside the bars, the EEG component and the associated instrumentation is named. While the sound patterns changed during the time, the light parameters were kept constant.

5.2 Participants

20 healthy people (mean age 38 years, 11 f/ 9 m) have participated in a Sensorium session separately. Ten of them had meditation experience with an average total practice time of 644 hours, the other ten were non-meditators. Eight from 10 meditators had more than 500 hours of experience. The sessions took place either in a small meditation room, or in the measurement cabin of our institute in which the feedback environment was installed. After signing their informed consent, they filled in a short introductionary questionnaire. Participants were seated on a meditation cushion. Five Ag/AgCl electrodes were attached to their body; one was a grounding electrode on the shoulder. ECG was measured with two electrodes between sternum and the left costal arch. One channel of EEG was measured with two electrodes between one mastoid and the position CPz of the 10/20 electrode system. After testing the signal quality the participant were instructed that the session will last for about 15 minutes in which they should sit relaxed with open eyes and just experience the lights and soundscape being aware that all changes of light and sound and all touches of an instrument will be initiated by a signal that was currently produced by their own body, i.e. by their brain or heart. Then, the session was started while the experimenter remained in the background or outside the chamber.

5.3 Results

5.3.1 Quantitative Results

After the session the participants had to fill in a final questionnaire assessing the subjective experiences during the session. This questionnaire was divided into two parts. The first was asking for tendencies in the emotional changes and changes in states of consciousness caused by the session. These were quantitative reports as answers were assessed in rating scales between -4 and 4. The participants had to describe their emotional state tending (or not) towards relaxation, wideness, harmony, happiness, satisfaction, luck and love. Table 3 summarizes the quantitative results, separately for meditators and non-meditators. The major difference between both groups is a better relaxing and widening effect for non-meditators. All differences between non-meditators and meditators of the emotional reports were non-significant. As this was a pilot study with very few subjects for each group, such comparison cannot be taken too serious.

Table 3: Quantitative statistical results of personal data and subjective ratings of the emotional effect after a Sensorium session. The two groups meditators and non-meditators were separated in this analysis.

Variable	Age	Meditation Experience	Relaxed	Wide	Harmo-nized	Happy	Content	Luck	Love
Meditators	46.6 (+/- 6.9)	643.9 (+/-342)	1.3 (+/-2.1)	1.7 (+/-1.6)	1.9 (+/- 1.7)	2.0 (+/- 0.9)	2.5 (+/- 0.8)	1.5 (+/-1.4)	1.9 (+/- 1.3)
Non-Meditators	29.2 (+/- 13.4)	0 (+/-0)	2.3 (+/-0.9)	2.5 (+/-1.1)	2.3 (+/-1.3)	1.7 (+/-1.1)	2.4 (+/-0.7)	1.7 (+/-1.0)	1.6 (+/-1.2)

The positive tendency of the emotional states for each participant separately is visible in Figure 13. The reason for the non-relaxing effect reported by some people in the first sessions could be associated with the distractive yellow heart beat light.

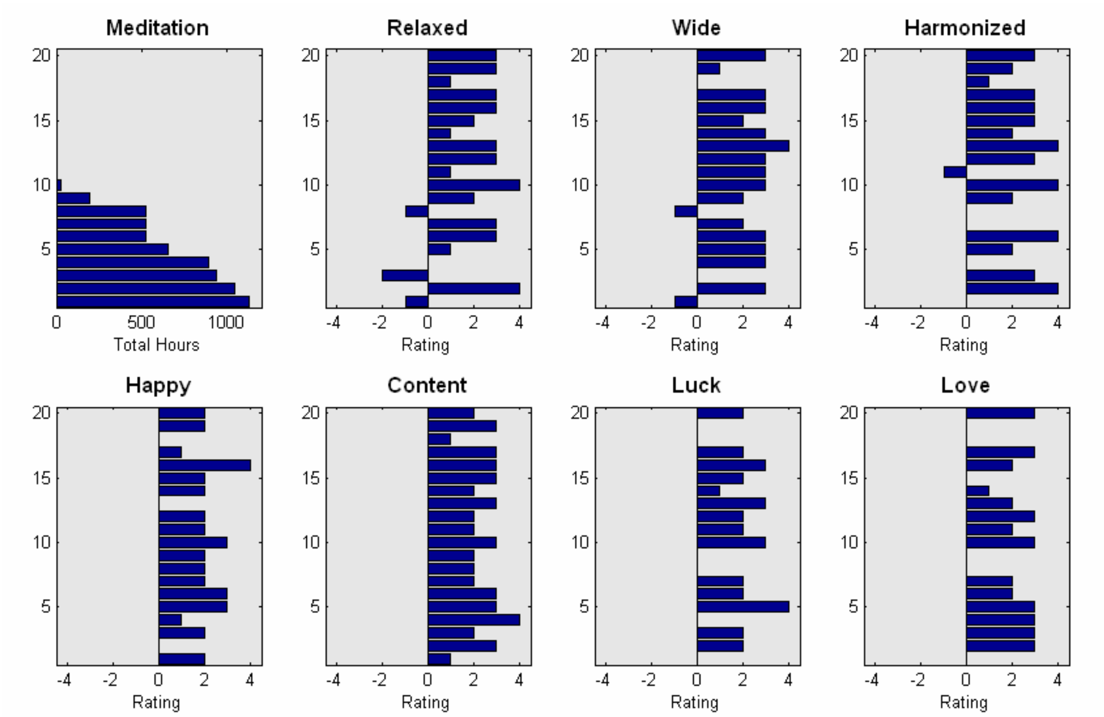
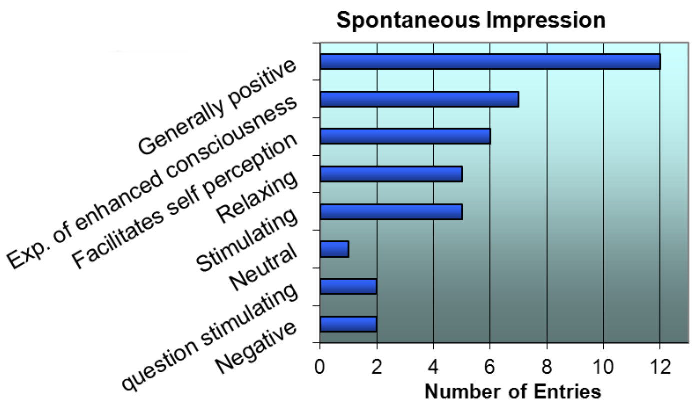


Figure 13. The upper left graph shows the total meditation experience for each of the 20 participants. The last 10 participants were non-meditators. The other 7 graphs show the ratings of the Sensorium session as a tendency towards the entitled emotional state. Zero means that there was no state change before and after the session. Negative values indicate a contrary effect.

5.3.2 Qualitative reports

The second part of the questionnaire collected qualitative data. The participants were given the opportunity to describe in their own words their personal impressions and feelings they had during and after the session. Regarding the general spontaneous impression after the session they predominantly gave positive feedback. 12 statements were generally positive like 'fascinating', 'interesting', 'novel, unique experience', or 'intensive experience'. In 7/20 participants the session initiated reactions like 'experience of an enhanced consciousness' and descriptions addressing the facilitation of self-perception were given by another 6 participants. Some impressions were inter-individually oppositional such as 5 persons described the session as relaxing and calming and other 5 persons described a stimulating and intensive experience. The relaxing effect pertains to a greater degree for the non-meditators (see Figure 14, left). Only one entry mentioned some discomfort by the flood of information and another person missed the obvious connection between inner and outer perception. These were the two negative entries.



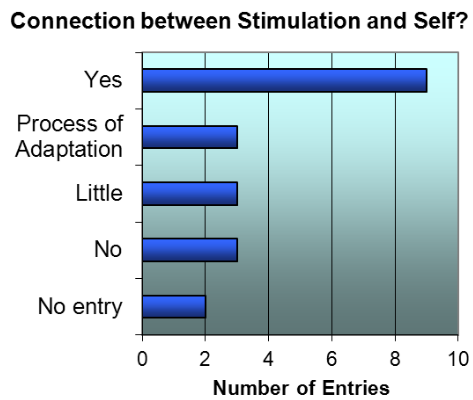


Figure 14. Left: Categorized responses to the spontaneous impression of the participants directly after a session. Right: Answers regarding the connection between the stimulation and the self.

Participants also were asked whether they had the impression of a connection between the light and sound stimuli and themselves ("Have you had the impression of a connection between the stimulation and yourself?"). 9/20 answered this question with yes, 3/20 with little, 3/20 said no and another 3/20 reported a process of adaptation.

In a further question, the effect on the body awareness was assessed. As illustrated in Figure 15, 15/20 persons experienced an increase of their bodily awareness. In six other entries, the experience of unity concerning to the "own" music and light was described. Four persons emphasized the effect of relaxation during the session. Two of the meditator participants felt themselves irritated through the flickering light which was used in the first sessions.

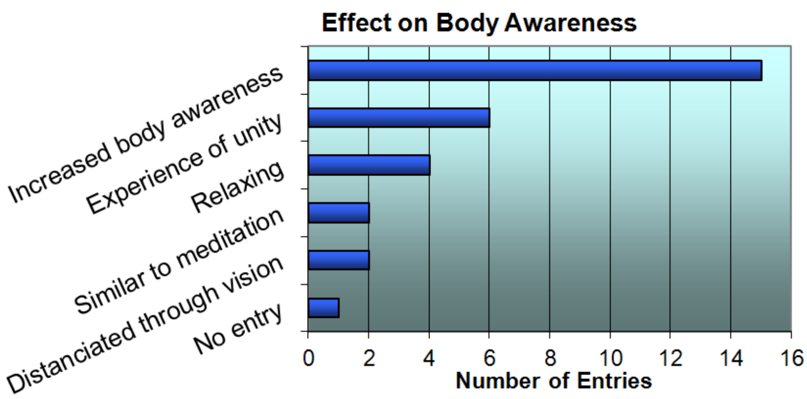


Figure 15. Answer categories of the question "What was the effect on your body awareness?"

Figure 16 shows the answers for the mental effect of the session. Despite the impressions were quite individual the mental effects were described positive in most entries. Important aspects were the effects of relaxation, quieting, and alteration of consciousness. The latter was reported by five meditators. Negative effects were again targeted towards the flickering light within the first sessions and the difficulty of a person to calm down the thought, which is generally a major difficulty in meditation.

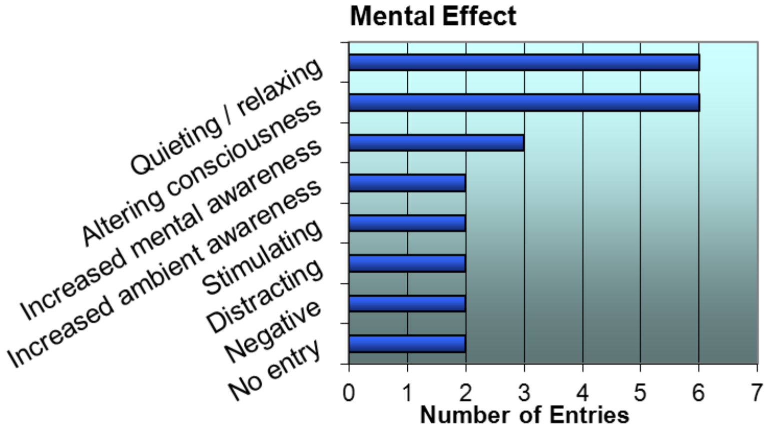


Figure 16. Answer categories in response to the question "What was the mental effect of the session?".

6. Conclusion and further progress

The Sensorium can be regarded as a novel approach of neurofeedback to create a unifying multisensory experience with the own body, the body rhythms and the self. In contrast to conventional neurofeedback devices the Sensorium focuses on the conscious experiencing of the complex body signals rather than on the self-regulation of a specific component.

This neurofeedback approach has been realized in two different fashions. 1) a wearable device called MediTrain, which is able to present electrophysiological signals from heart and brain in sound and light via headphones and colour LED glasses to the user. This device could be given to individuals as a home and portable version. It can be used for regular relaxation or consciousness enhancement by real-time self experience of the own physiology. The specific use and programs with this device will have to be tested and evaluated in further studies. 2) A solid installation was built using a PC, a stereo amplifier and speaker system and coloured spotlights. Here, the only wearable component is the physiology amplifier system that transmits the signals via Bluetooth to the computer. This system provides a high sound quality and illuminates the whole room controlled by body processes. It has been found that in contrast to the Meditrain device this system provides a more open and widening experience.

In a pilot study we have demonstrated that this sound and light environment is a powerful tool to guide people into various experiences and alter their consciousness, body and mental awareness in a positive and conscious way. The initial results encourage us to implement a self-stabilizing and health supporting intervention for patients with psychosomatic disorders and psychological disturbances but also for people without pathological diagnosis in the near future.

The tasks which will have to be done in further developmental and evaluative studies will be 1) to modify the software in order to provide an easy-to-use setup and control interface. 2) The hardware of the MediTrain device needs some modifications. Especially the sound quality of the MIDI chip will be tried to get improved. 3) A number of parameter studies have to be conducted. The SymPOSER system allows for a huge variety of different sound and light configurations. Settings have to be developed with respect to the aesthetic expression, the positive perception by the users and its specific effects on consciousness. We then intend to measure further subjects and compare their reports in order to continuously improve the sound and light feedback modes. We hope, that in future the Sensorium can provide a unique experience to both, healthy people and patients in a variety of locations such as meditation centres, wellness centres, and therapeutic environments.

7. Publication

This publication is currently under review for publication:

Hinterberger, T., "The Sensorium: A Multimodal Neurofeedback Environment," Special Issue on Advances in Human-Computer Interaction, submitted.

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