CENT - Computer Enabled Neuroplasticity Treatment: a modular, extensible platform for neurofeedback with lightweight wearable EEG devices

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ABSTRACT

Biofeedback/neurofeedback is a growing clinical field. Tools for administering feedback treatment tend to be proprietary and fixed/non-extensible. Thus there is a need for a biofeedback platform which is entirely open source, extensible and free. We present the Computer Enabled Neuroplasticity Treatment (CENT) platform to meet this need.

Keywords: neurofeedback, electroencephalography, ADHD, computer-enabled, Qt

Story/structure is:

1. Introduction + motivation
    - we needed a NFB platform and didn't find anything suitable (why not?)
    - we developed CENT platform at the same time as setting up the clinical trial
    - we aimed for lots of good things: modular, extensible, state of the art technology, effective but simple UI, minimal but extensible feature set
    - other systems exist but CENT fills a niche because...
2. Related work
    - Other neurofeedback platforms [DONE!]
    - Abundance of wearable EEG devices [DONE!]
3. Architecture - describe the tech. Show where to get it and the compatible parts
    - CENT-core
    - OV-signal proc [DONE!]
    - CENT-extensions
4. Validation
    - Malmi therapy
5. Discussion
    - We saw a need and filled it
    - Pros and cons
    - CENT vs. "Meditation toys"
    - Usage scenario
    - Future work: Interfacing with bestest systems (like MIDAS)
6. Conclusion: CENT platform is great, buy 6!

1 INTRODUCTION

Neurofeedback (NFB) is a growing field, with extensive clinical use, a large body of research literature, and applications also in performance enhancement, entertainment, and stress relief. However tools for administering feedback treatment tend to be proprietary and fixed/non-extensible. Thus there is a need for a biofeedback platform which is both robust, and entirely open source, extensible and free. We present the Computer Enabled Neuroplasticity Treatment (CENT) platform to meet this need.

1.1 Background

NFB, also called electroencephalography (EEG) biofeedback, is operant conditioning of specific temporal, spatial and frequency features extracted from scalp-recorded electrical potentials (Lubar and Shouse, 1976).

NFB has been described as "a mechanism that may be used to stimulate and/or regulate cerebral activity, which in turn may influence cognitive processing" (Vernon et al., 2003). The specific model of effect has been described variously as 'repairing' a presumed cause of disorder to 'normalise' behaviour, or instead as a tool to enhance cognitive states (see Gevensleben et al. (2014) for a thorough discussion). Either model can be applied in a clinical setting, while the latter enhancement model could also be applied in any non-clinical setting.

Part of its value is that NFB can be personalized to suit the specific clinical presentation, or performance enhancement requirements, provided that there is requisite theoretical and observational data to guide the personalisation. In clinical settings, the personalisation is often done by reference to quantitative or 'qEEG'-guided normative databases. Hammond (2010) discusses this in detail, illustrating the heterogeneity in qEEG patterns associated with symptoms and discussing the requirements and need for qEEG analysis guided by normative databases. Johnstone et al. (2005) provided a review of such databases, along with a review of qEEG profiles, which are "manifestations seen between genome and behaviour" that they term 'intermediate' EEG endophenotypes.

Beside the neurophysiological aspects of NFB, the psychology and experience of NFB are considered by many to be equally important. Calderon and Thompson (2004) have conceptualized biofeedback as a three-step process that consists of

- becoming aware of a physiological response,
- learning to control the response, and
- transferring control of the response to everyday life.

The first two steps of the model - becoming aware and learning to control the electrical activity of the brain - constitute NFB learning. The third step refers to transfer of the NFB learning, often measured in the literature by performance on a neurocognitive test of the treated function (e.g. attention) and/or self-reported symptoms.

Two of the more widely-used clinical NFB protocols are 'theta-beta' (TB) and 'sensorimotor rhythm' (SMR), which are those currently supported in the CENT platform. TB and SMR protocols are based on sub-second frequency-band features.

TB protocol assumes a model where theta power is elevated above normal, and therefore uses an inhibition target for theta power and a reinforcement target for beta power. EEG recording is often at a frontal site. The rationale behind TB training has been described in at least two different ways: as the rectification of cortical hypoarousal (Barry et al., 2003), and as the reinforcement of working memory (Vernon et al., 2003).

SMR protocol reinforces beta power, usually low or mid beta, often with an inhibition target for theta. The site is above the sensorimotor strip, often lateral, such that the beta oscillations correspond to the sensorimotor rhythm. The rationale for SMR training has been proposed as either facilitating attention (Vernon et al., 2003), or the improvement of sleep through an increase in beta spindles, with concomitant effects on cognitive function (Arns et al., 2014).

These protocols contrast with another widely-studied protocol, Slow Cortical Potentials (SCP) training, which feeds back the time domain DC component. SCP targets the Contingent Negative Variation (CNV) Event Related Potential, which Mayer et al. (2015) defined as "a slow negative shift over central sites that develops following the presentation of warning stimulus in expectancy of an imperative stimulus that

requires a response". SCP uses two opposed cortical regulation targets to be trained in random consecutive order. The TB and SMR protocols do not include such an explicit set of counter-poised targets to induce self-regulation, relying instead on a single target of reinforcement/inhibition, which is trained repeatedly.

Challenges The field of NFB makes progress, but in technical terms it does so slowly. The protocols introduced by Lubar and Shouse (1976) and others have remained unchanged for 40 years. As with any technology, progress relies not just on research, but also on adoption and exploration of the potential by developers. Rapid advances have recently been made in EEG-amplifier hardware and signal processing software, yet the software needed to facilitate open and rapid research and development in clinical NFB is lacking (see below). Opening the field calls for software which is robust, and entirely open source, extensible and free.

1.2 Neurofeedback software

Currently a large number of different NFB software packages exist, most of which are still actively used or still in development. The recent boom of wearable biosensors (such as cheap, commercial EEG devices like the Muse and Melon headbands) has also boosted the number of available personal NFB applications. Despite the popularity, very little literature exists reviewing NFB platforms. One report estimates the usefulness of various BCI frameworks for conducting NFB, and lists design considerations for such a system Huster et al. (2014). In this section we attempt to comprehensively cover different types of software packages are available for NFB.

All available NFB solutions share three basic characteristics which are: 1. a method of interfacing with an EEG device, 2. capability to process the acquired EEG data in real-time and 3. the ability to generate feedback for the user. Outside these parameters different software packages can have vastly different properties. For instance hardware devices supported, licensing, and intended usage all vary greatly between different NFB solutions. The NFB software can roughly be divided into two categories: clinical and non-clinical. The clinical category contains software that is solely intended for various NFB therapies (ADHD therapy being the most common). The other software packages are aimed more for personal cognitive neuromodulation and entrainment (such as mediation and stress management). We have compiled a list (table 1) which, to our knowledge, contains all of the currently available software packages intended for NFB.

Table 1 lists 33 NFB software, alongside their respective licenses and other information. The 'License' column indicates which license was used when the software was published. In some cases a software package was released with the source code but without a specified license, as noted by a question mark. The 'Merit' column refers to scientific merit, defined here as the highest ranking publication the corresponding software was used in. The rankings were extracted from the Finnish Publication Forum, which is a nationally-accepted quality assessment forum for publication channels. Rank values for publication venues are 0 (no rank assigned by the forum), 1 (basic), 2 (leading), and 3 (highest) [1]. The merit value indicates whether the software has been used in NFB related research. For instance the BioExplorer software has been used to study the increase local gamma and beta band activity through NFB Keizer et al. (2010) and the EEGer4 to study the effect of music on alpha/theta NFB Gruzelier et al. (2014).

The 'Last Update' column indicates the latest known time of publication for either software or documentation updates. This column indicates whether or not a project is still in active development. Twenty of the software packages are still clearly active (updates less than one year old), and seven more have received updates in the last three years, but the remaining six projects have been dormant for between four and twelve years.

Finally, in the last column the use case for each software (clinical vs non-clinical) is listed. The use case was determined on the basis of the developers' own descriptions from the web-page of the software.

Table 2 summarises data on license (open-source vs. proprietary) and intended use (clinical vs. non-clinical). This illustrates that the majority of available software are commercial with proprietary licenses. Although there are almost the same number of clinical and non-clinical software, all of clinical use software have a proprietary license. From this review, it is apparent that there is a clear lack of open-source solutions for clinical NFB. The closest option for such a platform would be the proprietary NeuroRT suite by Mensia Technologies, which like the CENT system, is built on top of the open-source

[1] For more information see `http://www.julkaisufoorumi.fi/en/publication-forum`

System	License	Merit	Last Update	Clinical use
BioEra	Prop.	1	2015-06-22	No
BrainBay	GPL	1	2014-12-03	No
BrainAthlon	?	1	2004-01-01	No
EEGMIR	?	0	2003-12-30	No
ElectricGuru	?	0	2002-01-21	No
BioExplorer	Prop.	2	2012-09-26	No
BioGraph Infiniti	Prop.	1	2013-06-05	Yes
BioTrace+	Prop.	2	2015-07-23	Yes
BrainFeedbackPro	Prop.	0	2015-11-19	Yes
TruScan Neurofeedback	Prop.	0	2015-11-19	Yes
BrainMaster	Prop.	1	2015-10-09	Yes
BrainPaint	Prop.	2	2012-01-01	Yes
Cygnet	Prop.	1	2015-11-01	Yes
eBioo	Prop.	0	2015-03-01	Yes
EEGer4	Prop.	2	2013-06-10	Yes
EventIDE	Prop.	0	2015-08-18	No
Mind Workstation	Prop.	0	2011-08-31	Yes
MindReflector	Prop.	0	2013-09-19	Yes
Neurofield	Prop.	1	2015-02-06	Yes
neuromore Studio	Prop.	0	2015-11-06	No
NeurOptimal	Prop.	0	2015-07-01	Yes
NeuroRT	Prop.	0	2015-11-04	Yes
OpenViBE	AGPL	1	2015-10-02	No
SmartMind3	Prop.	1	2015-01-01	Yes
Melon - Brain Training	Prop.	0	2015-02-28	No
Muse App	Prop.	0	2015-12-16	No
Neurosurfer	Prop.	0	2015-02-15	Yes
BrainWaveOSC	?	0	2014-07-30	No
OpenNFB	GPL	0	2015-11-19	No
WaveTuner	?	0	2013-10-16	No
AlphaTrainer	?	0	2014-05-20	No
Mindrun	MIT	0	2015-09-29	No
Resonanz	GPL	0	2015-07-23	No

Table 1. Currently available neurofeedback software packages

OpenViBE platform. However, there is no NFB software for clinical use that is truly open-source from end-to-end, including both the signal processing back-end and the patient management front-end.

	Non-clinical	Clinical
Proprietary	6	15
Open-source	11	0

Table 2. Division of use case and license in neurofeedback software packages

1.3 Wearable EEG sensors

In recent years there has been a sharp increase in the availability of ambulatory EEG sensors. This is partly due to technological advances, and also to the popularity of the quantified self movement. The quality of these devices varies from purely consumer-grade (also known as lifestyle applications) to more expensive but near laboratory-grade devices. The suitability of each device for NFB therapy must be tested, but the current trend looks promising as the devices are readily available and cheap compared to laboratory EEG.

The standard software that usually accompanies these devices seems to be more oriented for self

quantification and cognitive enhancement. For instance the MUSE band comes with an application that teaches meditation techniques. Devices like the MUSE, however, provide a communication protocol that allows other software to access the raw data of the device. Therefore, it is plausible that these devices can be used as an input to NFB software. The modification necessary would require that NFB software itself could be modified which further increases the need for open source solutions.

1.4 CENT platform

The CENT platform was developed to facilitate the CENT clinical trial of NFB treatment for adult ADHD, conducted at the University of Helsinki, Finland [2]. In the context of the CENT trial, the CENT platform was used with 25 patients, during approximately 40 NFB sessions of 1 hour per patient. Two separate models of EEG amplifier were supported during this trial, along with two NFB protocols (TB and SMR), in two different modes (normal and inverse). Thus in total eight separate conditions of NFB training were supported by the platform. More detail is given in section 3 below.

The CENT platform was designed to connect light-weight EEG amplifiers to a simple, easy-to-use interface for running NFB sessions. The platform's workflow is fixed but adaptable, with configurable settings for personalisation of the treatment, including:

- capability to modify the spectral values recorded at baseline, thereby increasing or decreasing difficulty of the task
- different games with different levels of stimulation and different 'look and feel'
- options to review performance

With the existing range of features, the platform demonstrates its utility for the task of clinical neurofeedback. Additionally, with an open, robust, modular architecture it is ideal for extension to add new features or explore other application possibilities.

Outline In the rest of this paper, we will first describe in section 2 the CENT platform, including the core architecture, the signal processing framework, and the options for adding software extensions. Then, in section 3, we will describe a validating example of how the platform was used. Finally in section 4 we discuss the implications for the platform, and possible future work and conclusions.

2 METHODS - ARCHITECTURE

2.1 Platform architecture

The CENT platform is built on Qt...

todo: platform technology

2.2 Signal processing

2.2.1 Overview of signal processing architecture

The signal processing back-end of the CENT system was implemented using the open-souce OpenViBE platform Renard et al. (2010). The OpenViBE platform consists of a visual modelling language (similar to LabView or Simulink) which enables the design of various signal processing protocols, called *scenarios* in the OpenViBE terminology. The scenarios can be drawn by connecting boxes representing various operations to each other in order to produce to a flowchart of how the data is processed. CENT integrates a fully functional version of OpenViBE which means that the original editor can be used to design new protocols or to modify the existing ones.

The signal processing back-end of the CENT system contains multiple OpenViBE scenarios. A list of scenarios required for a typical NFB session can be found in table 3. Scenario-files can be found in the *scenarios* subfolder of the CENT installation. Scenarios themselves are constructed using existing modules known as 'Boxes'. Boxes range from very simple (such as squaring each signal value) to more advanced (such as linear discrimant analysis or support vector machine classifications). Information between boxes is passed as streams of data. OpenViBE has multiple different streams but the two most important for the CENT system are 'Signals' and 'Stimulations'. Signals are simply chunks of EEG data

[2] Clinical trial registered with ISRCTN, DOI 10.1186/ISRCTN13915109

that contain a buffer of the raw voltage values and the sampling rate used to acquire them. Stimulations are similar to trigger codes in most EEG applications and can be used to convey meta information like classification results or signal quality. Most of the common EEG signal analysis operations can be completed using some combination of available boxes and streams. It is important to note that due to the open source nature of OpenViBE it is also possible to write new boxes for desired functionality.

cent_monitoring_and_noise.xml	Scenario for online monitoring of the signal and checking the signal quality
cent_baseline.xml	Baseline measurement
cent_generate_configuration.xml	A utlity sceneario used to generate configuration files required for the actual session
cent_game.xml	The main scenario for the therapy session

Table 3. List of OpenViBE scenarios used in CENT

Parameters for different boxes can either be set manually in the designer or they can be specified in a separate XML configuration file. Functionality of OpenViBE scenarios can be expanded using scripts written in Lua or Python languages. For more detailed explanation of box configuration see Renard et al. (2010).

Although the box system is very flexible and gives freedom in experiment design, the implementations of even simple routines tend to require many boxes. For example feature extraction of signal powers from few frequency bands can require the use of multiple boxes. Furthermore the implementation of these processes requires a certain level of knowledge regarding signal processing and might not be intuitive to the end user. For this reason the end user will not need to modify the OpenViBE scenarios in order to use the CENT system. Most of the necessary changes to the parameters can be done from within the CENT system and through configuration files.

The overall aim of the signal processing back-end is to classify the neurological state of the patient, based on power modulations in frequency bands of the EEG. Upper and lower band limits are defined by the protocol in use. In practice classification is done by first acquiring a 60 second baseline recording of resting-state EEG. In the subsequent session the current power values are compared to threshold values extracted from the baseline to generate classifications. Positive classifications occur when changes in the EEG power (registered by the signal analysis module and passed back to the CENT system) in relevant bands matches or exceeds (positively or negatively) the baseline thresholds. Positive classifications modify the behaviour of the game, to give contingent feedback to the patient who thus slowly learns to modify their neural patterns.

2.2.2 Scenarios

This section briefly describes the operation of each of the scenario files. Each scenario can be divided into functional sub-elements that correspond to a certain step in a typical BCI processing chain. More information on the behaviour of the sub-elements can be found in the Signal processing protocol section, where structure and behaviour of different components are described.

Monitoring and noise Monitoring scenario is responsible for displaying the live EEG and current noise level at the beginning of the therapy session. This scenario is mainly a tool for making sure that the electrodes are properly fixed and that the data streaming is working. Figure 1 shows the structure of the scenario. The scenario structure is relatively simple consisting only of acquisition client, filters and a noise calculator. The same structure is integrated into baseline and game scenarios.

Baseline Baseline scenario is used to determine the baseline frequency-band power values. During the baseline recording patient will be fixating on a cross displayed by the CENT system. Therapist screen will display the live EEG as well as the noise bar. Duration of the baseline recording is 60 seconds with 10 second offsets at the beginning and end of the recording. The recorded data is split to segments of 5 seconds and for each segment the power values are calculated using the same procedure as in the game scenario (this procedure is explained in greater detail in section NN). Finally the segments are are averaged to produce the final baseline values for the session. In addition to the baseline values a complete

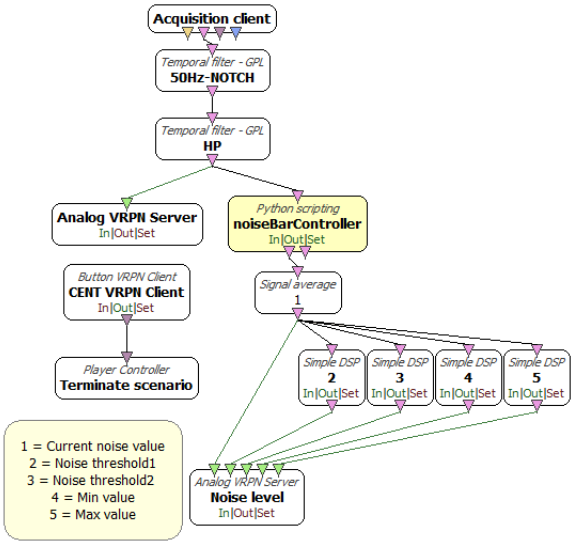

Figure 1. OpenViBE scenario for signal and noise check.

power spectrum is calculated using the entire recording. Both the baseline values and the spectrum are displayed after the baseline recording for quality assurance.

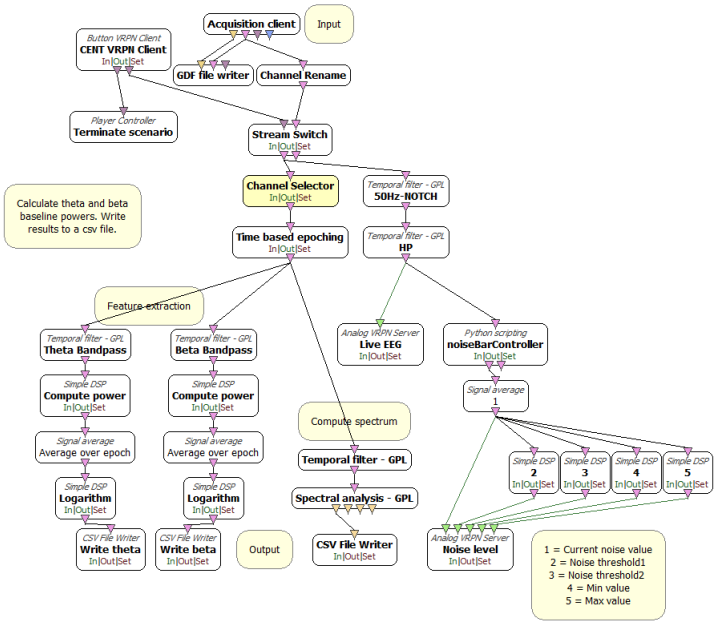

Figure 2. OpenViBE scenario for baseline measurement.

Generate configuration Configuration generation scenario is a utility tool used to generate configuration files for the feature extraction in the game trial. The scenario displays no data and the execution only lasts seconds. The scenario takes the baseline values calculated in the previous section and uses them to automatically configure the main game trial. Figure 3 displays the corresponding OpenViBE implementation.

Game Game scenario evaluates the current mental state of the patient and send information back to CENT. The scenario calculates power values for theta and beta using 1 second epochs and compares them to the values calculated during baseline measurement. The game scenario does not actually do anything

Figure 3. OpenViBE scenario for writing configuration files.

related to the game as the actual game mechanics are handled by an external plugin. The OpenViBE implementation of the game trial is visible in figure 4

2.2.3 Signal Processing Protocol

NFB signal processing protocol is closely related to the protocol used with brain-computer interfaces (BCI). It thus follows that the signal processing operations performed in a NFB session can be described by borrowing terminology from the field of BCI. In BCI a typical signal processing protocol is divided into four different steps: preprocessing, feature extraction, classification and translation. Preprocessing consists of removing noise and other artifacts from the signal. Feature extraction removes unecessary parts of the signal and classification assigns one of the predefined classes to the incoming signal. Finally the translation performs the action related to the assigned class (such as moving a cursor etc.). In NFB instead of a translation a feedback signal is sent back to the patient i.e, the game reacts to the current neural state. Different signal processing sections of the game scenario have been highlighted in figure 4. The operation of each section is covered in the following sections.

Preprocessing The EEG signal is passed into OpenViBE through a custom acquistion driver provided by the manufacturer of the EEG device. This driver can send both the EEG data and Stimulation messages to OpenViBE. The EEG device (Enobio) samples the data with internal sampling rate of 250 Hz which is then passed as packages containing several samples to the OpenViBE. The packet size in OpenViBE terminlogy is called a 'chunk' and the size of the chunk can be specified in the software. Multiple chunks can be combined in an epoch of specified length in seconds. Almost all of the OpenViBE scenarios start from the 'Acquisition client'-box which receives data from the acquistion server running under CENT. Acquisition is not a separate scenario but a part of all the signal processing scenarios of the CENT system. Incoming EEG signal is also saved to a GDF file for later analysis. In addition to the data, also the resulting classification labels (stimulations) are registered for each epoch. None of the filters used in visualization or feature extraction are applied to the saved data.

Visualization and noise measurement Visualization and noise measurement is used in all of the signal processing scenarios (with the exception of configuration writing). The EEG signal is transmitted from OpenViBE to CENT using a analog VRPN server. Because the EEG signal picks up a lot of noise originating from physiology and the surroundings two filters are applied. First one removes the 50Hz power line interference using a butterworth notch filter (order: 4, stop band: 40-60Hz). Second filter removes the low frequencies physiological artifacts and signal drift. Second filter is a 4th order high pass with a cut-off frequency of 0.5Hz. Noise monitoring is implemented as a separate Python box which provides information to the current signal quality.

Feature extraction Feature extraction, in BCI terminology, means extracting the parts of the incoming signal that contain the information relevant to the task. Feature extraction can be thought of as dimensionality reduction where unnecessary components of the signal are removed in order to improve the classifcation accuracy and robustness. In CENT system both the baseline and game scenario have feature extraction structures. In the baseline scenario feature extraction calculates the power of theta and beta bands. Game scenario also computes the two power values but in addition it also compares these values to the baseline values.

Features are extractred from 500ms segments of EEG with 500ms interval. Power values for the two bands in each epoch are extracted using two 4th-order IIR butterworth filters. By default the passbands are the literary values for theta and beta. Alternatively, the two bands can be configured according to the individual alpha frequency of the patient by using configuration files. The use of individual alpha peak frequency is discussed in section NN. Once the incoming signals have been filtered the voltage values are squared and averaged over the epoch. Finally a logarithm is taken to produce the final power values.

Classification Classification assigns the extracted features to one predefined class according to a predefined mathematical rule. In CENT system these classes are ADHD and not-ADHD and the classification is done with 1D Linear Discriminant Analysis (LDA) classifier. Both of the extracted features are classified as either OVTK_StimulationId_Target (for not-ADHD) and OVTK_StimulationId_NonTarget (for ADHD). Because the version of OpenViBE used in CENT only supports binary classifiers (classifiers with only two possible outputs) the two classifier outputs are combined using a voting classifier implemented in Lua script (luaVoter.lua).

2.2.4 System Configuration

As stated earlier the parameters of the signal processing protocol can be configured using XML formatted configuration files. Configuration files can be found in the IEP directory. The adjustable parameters are listed below along with a description of what they do.

Box configuration

noiseBarController Can set parameters for noise detection. Adjustable parameters are EOG threshold and EOG window. Noise detection is also capable of detecting EMG activity but this feature is not currently used.

Time Based Epoching Can set the duration of EEG epochs used in classification. Default value is 500ms with 500ms interval between epochs. Epoch length defines the amount of data used for each classification but also sets the interval of feedback to the patient

Theta/Beta Bandpass Can adjust the bandpass filters used to calculate powers in theta and beta bands. See IAF section for configuring the passbands according to the individual alpha frequency.

Classifier processor Can change the classification algorithm and parameters for the two classification processors. The two currently supported algorithms are Linear discriminant analysis and Support vector machines.

2.2.5 Individual alpha frequency

In EEG literature the oscillatory activity of the brain is divided into different frequency ranges denoted by letters from the greek alphabet. The activity in different frequency bands correlates to different mental activities. These values, however, represent a grand average over a large population and might not produce the best possible result in NFB when applied to an individual subject. Earlier research suggests that individual variations in the frequency ranges exist among subjects and there is a method for assigning individual frequency bands for different subjects Klimesch (1999).

In CENT signal analysis individual frequency bands will be determined in the preliminary calibration session of the CENT system to a particular subject. Calibration will consists of recording EEG in eyes-closed condition for few minutes and then analysing the data with an IAF tool also provided in the software package. Alpha peak is extracted from the data by first computing the spectrum and then looking for a peak value in the 7-14 Hz range. Once the peak value has been found other frequency bands can be computed, relative to this peak value (for more details regarding this method see Babiloni et al. (2010)). Once IAF corrected frequency bands have been calculated they can be written into a OpenViBE box configuration files and used in feature extraction. Should the IAF frequency bands not be available or if the calibration fails, frequency bands from the literature are used instead.

2.3 Software extensions

2.3.1 Games inside the platform

describe the system of including games in the platform (much of the info already exists in docs?) describe those gamess that are packaged in this release

2.3.2 Applications integrated through platform menu

describe how to add menu-launched applications, and why (because they will have access to certain session-specific variables like the location of current users data)

2.3.3 Additional applications

describe applications that exist outside the platform, e.g. IAPF calculator, CENT recapper, MappingTool for hashed username retreival

3 RESULTS - VALIDATION

3.1 Clinical trial

We conducted a randomised controlled clinical trial of neurofeedback therapy intervention for ADHD/ADD in adults. The trial's main research aim was to focus on the model and internal mechanics of neurofeedback learning, to elucidate the primary role of cortical self-regulation in neurofeedback.

Trial Registration The trial was registered with ISRCTN as "Computer Enabled Neuroplasticity Treatment (CENT)", ISRCTN13915109.

3.1.1 Methods/Design

The intervention consisted of neurofeedback treatment with waiting list control group. Treatment involved 40 sessions, two-five sessions per week with five-seven units of training in each one hour session. Training involved either theta/beta or sensorimotor-rhythm protocols. The protocols were adapted by novel addition of an inverse training condition to promote self-regulation. Follow-up will consist of self-report and executive function tests.

The individual alpha peak frequency (IAPF) of each participant was estimated from band power analysis of eye-opened and eye-closed baseline conditions, following Lansbergen et al. (2011). The boundaries of each EEG frequency band for each participant are defined with respect to IAPF, e.g. theta is IAPF$\times$0.4 to IAPF$\times$0.6.

After randomisation between treatment and control groups, we assigned participants in the NFB treatment group to either TB or SMR training based on their IAPF-adjusted theta/beta ratio. Those with theta/beta ratio $>$1 (n = 9) received reinforcement for simultaneous increase in beta and decrease in theta (over power estimated from per-session baseline) at electrode Fz. The rest (n = 16) got reinforcement for increase in SMR and decrease in theta at electrode C4. Band powers within the NFB protocols are adjusted by IAPF.

NFB interventions were standardised by scheduling of the training sessions: session duration was fixed; and training blocks per session, sessions per week, timing of the break from training, and total duration of training were all constrained to equalise the intervention. Treatment group participants began their treatment by being briefed about all aspects of the NFB protocols, e.g. length, frequency, purpose. Outcome measures were taken when all participants in the treatment group had completed 40 sessions NFB.

Ethics Written informed consent for participation was obtained from all participants before entering the study. The protocol followed the Declaration of Helsinki for the rights of the participants and the procedures of the study. An ethical approval of the present research protocol for all participants was obtained from The Ethical Committee of the Hospital District of Helsinki and Uusimaa, 28/03/2012, 621/1999, 24 §. Participants were not remunerated.

Setting Intake and outtake measurements were conducted at University of Helsinki campus. Treatment was administered at partner clinic Mental Capital Care Oy, Helsinki.

Randomisation Randomisation used a two-step procedure: randomisation of half of recruits, followed by adaptive allocation of the remainder to minimise baseline differences in prognostic variables.

Blinding Due to waiting list control design, trial was not blinded.

Participants 54 adult Finnish participants (29 females) were recruited after screening by psychiatric review. They had mean age 36 years (std.dev. 10 years), with 44 ADHD and 10 ADD diagnoses.

Measurements Participants' symptoms were assessed by computerised attention test and self-report scales, at intake and outtake. Performance during neurofeedback trials was also measured.

3.1.2 Results

Participants were split between treatment and control groups. Following random group assignment, treatment began September 17, 2012. Of 54 inducted to the trial, eight dropped out from waiting list group, and two from treatment group.

Implementation In practice, NFB training consisted of 40 sessions (range: 38-41) during two to four months. There was a mid-training break of nominally two weeks. Patients came to the sessions two to five times a week. One session lasted 1 hour, subdivided into self-report of mood, excitement, hours slept and hours awake; electrode attachment; baseline measurement; five to seven units of five minute NFB trials; and debrief including self-report of effort and frustration. During each session, patients played different NFB 'game' trials during which they got immediate visual reinforcement for classifier-matching states in their EEG. The scores per game trial are baseline-adjusted and averaged per session to form characteristic LCs. The content and purpose of each training session followed a phased timeline:

1. Tutorial stage, for becoming accustomed to NFB, two practice sessions: participants were given normal NFB trials with baseline thresholds adjusted by a constant factor to make the training easier;
2. Beginner stage, for NFB training, 18 sessions up to halfway break: normal NFB with non-adjusted baseline thresholds;
3. Intermediate stage, for learning to self-regulate, ten sessions from half-way to session 30: normal training blocks were gradually reduced in number to half per session, and inverse training blocks introduced in their place;
4. Expert stage, for transfer training, ten sessions until session 40: as Intermediate stage, but also with one to two 'transfer' trials with no feedback stimuli.

Initial analysis showed that, compared to waiting list control, neurofeedback promoted improvement of self-reported ADHD symptoms. Additional detailed analyses are ongoing.

3.2 CENT platform in use

describe characteristics of using the platform, good e.g. flexibility, adding extra apps as desired, bad e.g. bluetooth streaming sucks

The CENT platform initially featured the two games described in 2.3.1, **simple ball** and **floating ball**. This was expanded *during* the trial, to include a **movie player** game (developed by BLStream), and a game called **Astrocomet**. Astrocomet was designed initially for the commercial market, and adapted by the developer **Ludocraft** to work as a NFB game according to specifications provided by the lead author. Ludocraft then integrated the game to the CENT platform using the standard approach defined in the documentation.

The CENT platform was thoroughly tested before deployment, so no software bugs were found during the trial. However, the system acquired data from the Enobio EEG amplifiers by bluetooth streaming connection, which seemed to become less reliable over time and several NFB trials failed due to lost connection. In an effort to fix this, we upgraded the EEG amplifiers to the next generation model, making the hardware switch during the mid-way break in training. The software corollary was the requirement for a new set of OpenVibe scenarios. All aspects of the upgrade, including resumption of training, went smoothly.

4 DISCUSSION

- We saw a need and filled it
- Pros and cons
- CENT vs. "Meditation toys"
- Usage scenario
- Future work: Interfacing with bestest systems (like MIDAS)

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4.1 Conclusion

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ACKNOWLEDGMENTS

Author credits:

- BC co-designed the platform UI, designed the clinical trial where it was used, developed the Matlab tool for results review, and co-authored the draft
- JT co-designed and developed the OpenVibe 'scenarios', co-authored the draft, etc, etc [insert what you did]
- TI tested and debugged the CENT platform, co-authored the draft, etc, etc [insert what you did]

The authors thank the software engineers:

- Arthur Zielazny co-designed the platform UI and the CENT Qt framework
- Robert Rabenel co-designed and developed the CENT Qt framework
- N. N. co-developed the CENT Qt framework(?) and the movie player application

Testers and contributors: Authors would like to thank Elisa Kallioniemi, Markus Kivikangas, Christina M. Krause, Laura Kauhanen, Mona Moisala and Marko Repo for contributions during design, development and testing.

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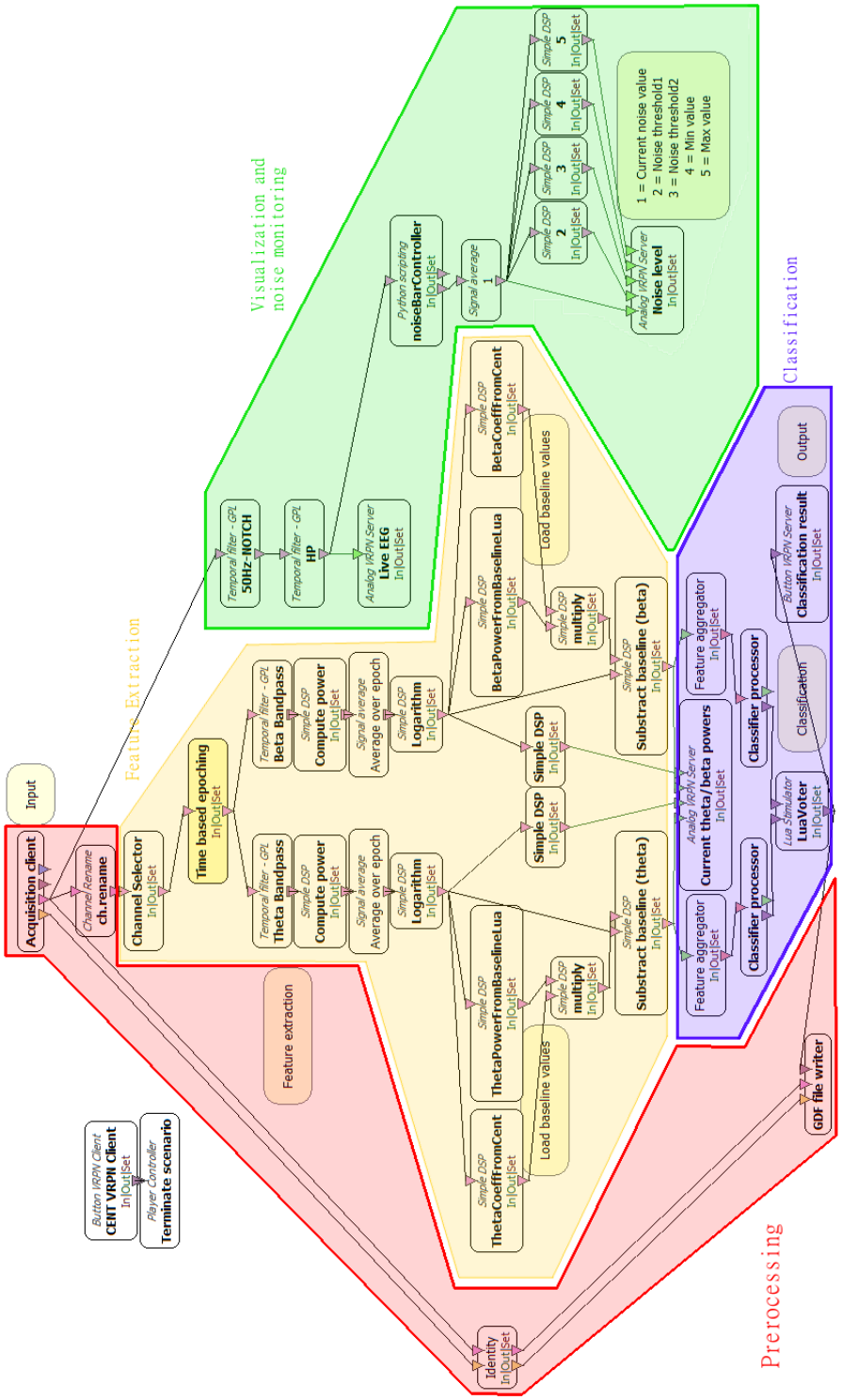

Figure 4. Signal processing sections of the game scenario.

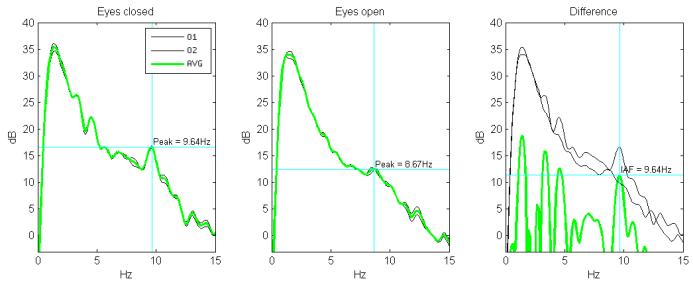

Figure 5. One method for calculating the individual alpha frequency (IAF).