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A Simple and Practical Sensorimotor EEG Device for Recording in Patients with Special Needs

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Keywords: Electroencephalography (EEG), Portable EEG, Sensorimotor Rhythms, Event-related (de-)Synchronization (ERD/ERS), Sensorimotor Disorders, Cerebral Palsy (CP).

Abstract: In studies involving patients with special needs, the use of electroencephalography (EEG) recordings is among the most delicate measurement modalities. The quietness needed and the long preparation time can be challenging especially in young ages. Furthermore, the invasive appearance of the instrumentation involved is not appealing and can raise distrust in patients. We developed a customized EEG device which adresses these issues by merging commercially available EEG hardware with an unobtrusive headphones design. The resulting device has very short preparation times, non-clinical appearance, and delivers adequate data quality with respect to recording of sensorimotor rhythms. Our device was employed in a study investigating sensorimotor-related brain activity in adolescents and adults with cerebral palsy (CP) conducted at a day-care center. Experimenters reported convenient data collection and overall acceptance of the system among patients. The changes in sensorimotor rhythms over time during a hand motor task meet the observations described in the literature, supporting the functionality of our EEG device for the assessment of sensorimotor-related measures of brain activity in patients with sensorimotor disorders of neuronal origin.

1 INTRODUCTION

In clinical studies, researchers need to be aware not only of the underlying (neuro)physiology specific to a clinical group but also of how experimental data can be successfully collected in patients with special needs (Vuckovic et al., 2015). This is particularly evident in patient groups involving children or elderly population, but also in individuals suffering from behavioral and developmental disorders, such as autism, cerebral palsy (CP), and sensorimotor disorders in general. Several issues are common among these patient groups: (1) reduced attention span and highly fluctuating concentration (2) impaired motor function and consequent inability to execute some experimental tests, (3) cognitive and sensory impairment (4) motoric restlessness and sudden involuntary movements typical for dyskinetic cerebral palsy, (5) worry about obtrusive measurement equipment that is associated to earlier clinical examinations and negative and unpleasant experiences, especially in patients that went through long medical treatment.

In most cases a careful tradeoff between what the patients can bear and the amount, type as well as quality of collected data has to be made. In this regard, whilst electroencephalography can be a valuable primary or complementary experimental modality, it is often declined as: (1) EEG equipment used in experimental studies can look obtrusive and raise distrust amongst patients. Researchers risk therefore that patients decline to participate in the study. (2) Proband preparation exceeds at least 15 minutes which is above endurance of many individuals from above mentioned patient groups. (3) The data collected can be strongly affected by different types of artifacts (e.g. muscular interference due to restlessness) and cannot be considered in the evaluation.

When looking at commercially available EEG systems, currently the market offers four established categories: (I) medical systems for clinical monitoring and diagnosis, (II) scientific systems for experimental research and Brain-Computer Interfaces, (III)

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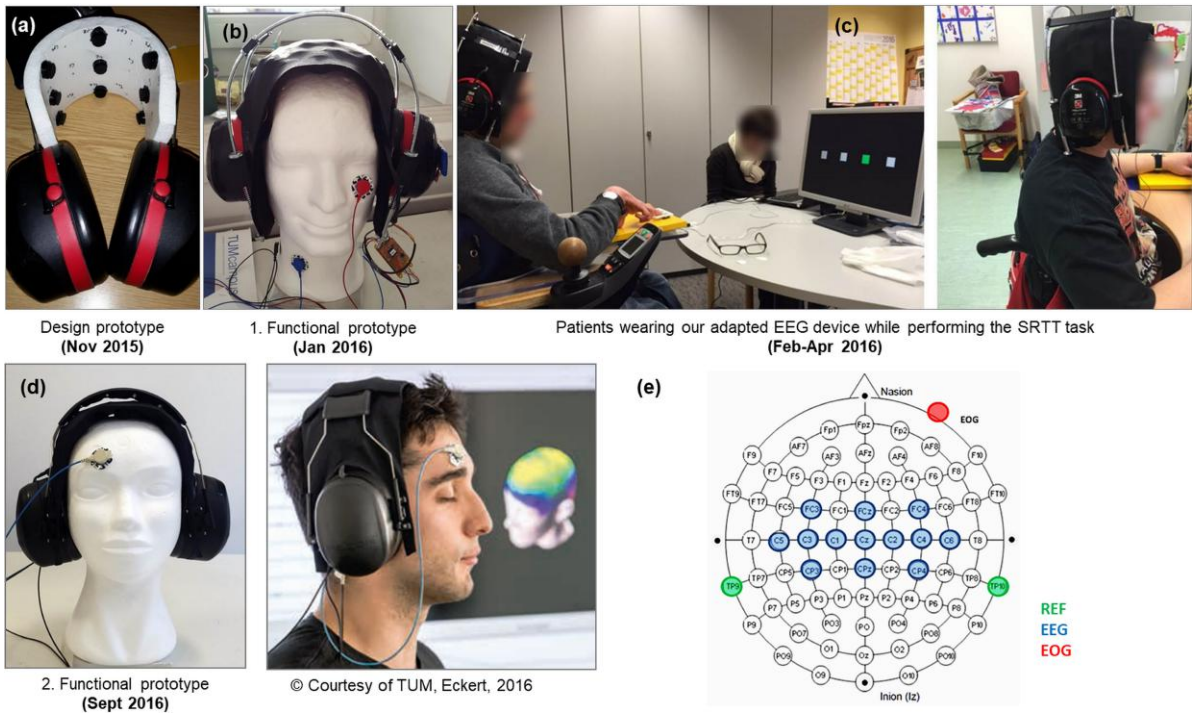

Figure 1: History of development of our adapted EEG device. 13 semi-dry EEG channels covering sensorimotor areas are embedded into the elastic sheet between the earpieces. Note the optional electrooculogram (EOG) channel attached to the cheek or forehead for capturing vertical or horizontal eye movements. (a) Design prototype; (b) 1. functional prototype used in the studies described in this paper; (c) patients wearing our EEG device while performing the SRTT task in the first data collection session; (d) 2. functional prototype, developed in follow-up work; (e) Electrodes positioning of our adapted EEG device according to the international 10-20 system (Homan et al., 1987).

consumer systems for gaming and entertainment, and (IV) open-source Do-it-Yourself (DIY) setups. A fifth category is currently gaining increasing attention. These systems aim to close the gap between scientific and consumer systems and focus on easy handling, short preparation times, portability, and high wearing comfort.

This paper aims at making a contribution in line with this new category of EEG systems. In collaboration with the medical faculty we developed an ease-of-use, unobtrusive EEG device to be employed in the study of sensorimotor disabilities in patients with motor disorders. Envisaged in particular were adults and adolescents with a diagnosis of CP, a medical condition characterized by motor deficits caused by damage to the developing brain pre-, peri- or post-natal. Event-related synchronization/desynchronization (ERS/ERD) of the brain mu- and beta rhythm constitutes a neuronal correlate of motor action (Pfurtscheller and Da Silva, 1999). ERS/ERD may constitute a useful measure in the study of motor disorders of neuronal origin as well on the evaluation of therapy efficacy. Measurement of ERS/ERD was here measured during the execution of a hand motor task adapted from the Serial Reaction Time Task (SRTT) (Robertson, 2007).

2 CONCEPT, TECHNICAL REALIZATION, AND HANDLING

2.1 Requirements

As mentioned above the device here described was developed having in view the investigation of sensorimotor deficits in patients with CP. These present impaired muscular imbalance and increased muscular tonus that results from neuronal damage during brain development (Rosenbaum et al., 2007). Deficits are not progressive but persist throughout the patients' life. The degree of impairment varies depending on the brain areas affected and motor limitations are often accompanied by learning difficulties, attention problems, perceptual impairments, speaking difficulties and/or epilepsy. The multi-symptomatology in CP makes it a challenging condition to research and demands a multidisciplinary approach when investigating possible rehabilitation strategies. From

the lifelong medical follow up of patients it becomes clear that, whilst primary medical care provides vital treatment, patients need for inclusion is likely to benefit strongly also from the collaboration between medical expertise, neuroscience and advances in neurotechnology.
Technical adaptations were performed in a commercially available EEG system to conform to the following requirements:

- unobtrusive visual appearance that is not immediately associated with a clinical examination device.
- short preparation time: < 5 minutes.
- comfortable wearing for up to 30 minutes.
- easily adapted to different head sizes (from children to adults).
- electrodes positioning according to the 10-20 system (Homan et al., 1987) and covering the majority of sensorimotor areas.
- resistance to hygienic treatment.
- positive reception/good acceptance of the device by the participants.

2.2 Design Concept and Realization

Standard EEG recording equipment for scientific and medical purposes usually consist of a cap of flexible fabric with electrode placeholders, an amplifier connected to the electrodes via cables, and a computer connected to the amplifier recording and storing the data (e.g. BrainProducts actiChamp). The cap setup allows for flexible and precise positioning of the electrodes and is comfortable to wear. However, despite the high data precision achieved with these systems, some technical aspects make them non-optimal for recordings in some clinical populations. Most such systems use gel-based electrodes which require long setup times, exceeding the patient's endurance, and are as such not usable. Alternative systems use dry electrodes (e.g. Guger Technologies g.Nautilus) which significantly reduce preparation time. However, dry electrodes require firm contact pressure of the electrode on the scalp to yield good conductivity and as such significantly reduce wearing comfort. Moreover, dry electrodes are more susceptible to noise and measurement artifacts than gel-based electrodes. At last, the chin strap for closing and tightening the cap can cause feelings of suffocation and might not be tolerated by some patients. Also, the chin-strap makes signal acquisition prone to artifacts resulting from head and face movements as well as talking. Patients with CP, especially adolescents, are unlikely to sit still for long time. Some systems do not make use of a cap setup, but rather a frame or flexible headband design, such as the Quasar HMS, or the emotiv EPOC. These systems however were also inadequate for the envisaged group, partially because of their obtrusive appearance, partially because of limited flexibility for electrode positioning. None of the commercially available systems fullfilled all requirements which motivated the need for a costumized design.

As a compromise between flexible cap and stiff frame setup which does not require a chin strap we decided for a design mimicking headphones (see Figure 1). Headphones have natural unobtrusive appearance as people are familiar with using them for music listening. Furthermore, headphones apply contact pressure around the ears which has proven comfortable to wear and allow for tight sit. In addition, the headphones allow the recording electrodes to be embedded within their headband and consequently to be naturally positioned over motor areas, necessary to assess sensorimotor-related brain activity.

As for sensors and electronics we decided to reuse a worn-off emotiv EPOC device. Despite the original purpose of the emotiv EPOC for gaming and entertainment, there have been numerous scientific papers making use of the system. The system has systematically been validated with regard to the use for scientific purposes, e.g. in (Hairston et al., 2014) and (Debener et al., 2012). This shows that despite lower signal quality, the system delivers usable data in a wide spectrum of applications. The emotiv EPOC sensor technology makes use of a semi-dry solution, namely felt pads soaked with saline solution establishing conductivity between the proband's scalp and the gold-coated electrodes. The electrodes require a certain contact pressure but the soft felt pads allow for comfortable wearing. The emotiv EPOC headset is a one-size for all frame with a fixed positioning of the electrodes. Its original layout has mainly channels over the pre-frontal areas.

We freed sensors and electronics from the original plastic frame and included the raw modules into our headphones setup. A flexible two-layer sheet made of washable fabric was mounted in between the left and right earpiece, which are held together by two curved threaded metal bars. The two-layer sheet embeds and hides 13 (of original 14) EEG electrodes and the connecting cables to the electronics. One channel was spared for capturing vertical eye-movement via electrooculogram (EOG) signals (see Figure 1). This allows for either online or post-hoc eye-movement artifact reduction. The right earpiece was used as the housing for electronics, leaving enough space to fill

it with rubber foam for sustaining sound insulation and ensuring no contact of the proband's ear with the electronics. The electronics communicates wirelessly with a transceiver connected via USB to a recording computer. The original reference channels were replaced by longer cables connectable to the proband's left and right mastoids via electrocardiogram (ECG) patches. Miscellaneous parts to assemble the whole system were 3D-printed.

The emotiv EPOC hardware is compatible with open source recording software, such as the OpenVibe framework (Renard et al., 2010). This allows for convenient access to raw signals and high flexibility in experiment design and implementation. Proband preparation takes $<$ 5 min.; after initial preparation, electrode impedances stay stable for at least 30 min. A simple mechanism allows for quick ($<$ 5 min.) adaptation of the headset to different headsizes (˜52-58 cm diameter). For hygienic reasons, felt pads can be replaced and the electrode sheet as well as the earpieces be sanitized. More technical details are listed in Table 1.

Table 1: Facts and figures. Some figures (*) were taken from the emotiv EPOC specification[1].

Sensors and channels	
Number of channels	**18** (13 EEG, 1 EOG, 2 Reference + 2 axis gyrometer)
Sensor technology*	Semi-dry saline soaked felt pads
EEG channel labels (10-20 system)	FCz, Cz, CPz, FC3, C1, C3, C5, CP3, CP5, C2, C4, C6, CP4, EOG, REF1, REF2
Electronics and signal acquisition	
Sampling rate*	2048 Hz internal, filtered and downsampled to **128 Hz**
Frequency response*	**0.16 - 43 Hz**
Resolution*	**14 bit** per channel (0.51 μV)
Wireless data transmission*	emotiv proprietary 2.4GHz wireless (custom USB receiver)
Usability	
Internal battery power*	Li-poly battery, 680 mAh, $>$ **12 hours**
Maximum distance to wireless transceiver	up to **10 meters**, 1 meter recommended to avoid data packet loss
Stability of electrode conductivity	tested up to **30 minutes** without re-applying saline solution
Proband preparation time	approx. **5 minutes**
Applicability with respect to head size	approx. **52-58cm** diameter
Adjustment to different head sizes	$<$ **5 minutes**
Price per device	in total approx. **US$799** (emotiv EPOC US$ 699 + <US$100 miscellaneous)
Costs for spare parts per data recording / proband	approx. **US$1** (3 single use ECG patches, 13 felt pads)

3 EVALUATION AND RESULTS

3.1 Data Quality Evaluation in SRTT Task Protocol

For signal quality evaluation, data was collected from one healthy subject performing the SRTT task in two separate sessions. In the experiment, the participant was presented 1 out of 4 possible targets on a computer screen and had to respond with a corresponding right hand key press. In total 40 trials were collected per data set with an inter-trial pause of 10 seconds. Each trial consisted of the visual cue presentation and the subsequent participant response. The first session was recorded using a Brain Products actiChamp 32-channel gel-based active electrodes setup with 500 Hz sampling rate. All leads were referenced to the average of left and right mastoid and impedances were kept below 5kΩ. The second session took place on a different day and was recorded using our adapted EEG device with 128 Hz sampling rate. Also here, all leads were referenced to the average of the left and right mastoid; electrode connectivity was tested using the Emotiv TestBench Software. Sensors were adjusted until connectivity reached the 'green' level (corresponds to an impedance of $<$220kΩ according to a test performed by Badcock *et al.* (Badcock et al., 2015)).

All data processing was carried out in MATLAB, in part using functions provided by the EEGLAB toolbox (Delorme and Makeig, 2004). First, the data from the actiChamp device was downsampled to 128 Hz to make it comparable to the data collected with the adapted device. Then, each dataset was high-pass filtered using a zero phase Hamming Windowed sinc finite impulse response (FIR) filter with cutoff frequency of 0.5 Hz. The data was then segmented into epochs, time-locked to the moment of key-press. No epochs were rejected for further analyses. For com-

[1] https://emotiv.com/store/compare/

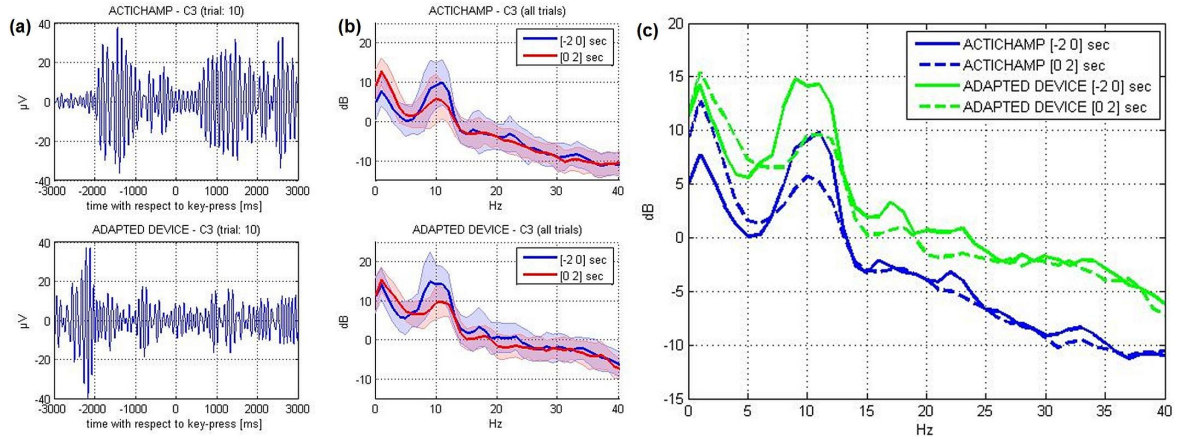

Figure 2: Panels (a): Depiction of bandpass-filtered (8-13 Hz) signal recorded at position C3 for trial 10, for both datasets (actiChamp in upper panel, adapted device in lower panel). Panels (b): Power spectrum of channel C3 separately computed on 2 seconds before and 2 seconds after the key-press. Thick lines represent the average power spectra across trials (n=40); shaded backgrounds represent the single standard deviation across trials. Panel (c): Comparison of average power spectra of both devices.

parisons we focused on channel C3, located approximately over the right-hand related contralateral motor cortex, and which therefore we expect to show a strong sensorimotor effect (mu-power suppression, see (Pfurtscheller and Da Silva, 1999)). Figure 2 (a) shows the mu-bandpass-filtered signals (zero phase Hamming Windowed sinc FIR filter with cutoff frequencies 8-13 Hz) of channel C3 exemplarily from one single trial. In both datasets suppression of mu-power around the time of key-press can be observed. In panel (b) the power spectra of channel C3 are depicted, both for the period of 2 seconds before and 2 seconds after the key-press. The spectra show that power suppression is mainly concentrated on the mu-band. The amount of suppression is quantitatively similar in both datasets. Also, the standard deviation of trial-to-trial power spectra does not differ significantly across the two devices. Panel (c) shows the comparison of average power spectra of both devices. We observe approximate 5dB difference between the power spectrum of the actiChamp and the adapted device which is relatively uniform across the relevant spectrum (0-40Hz). We interpret this as added white noise in the adapted device due to lower electrode conductivity.

ERD/ERS was computed from the mu-bandpass and beta-bandpass filtered signals according to Pfurtscheller's method (Pfurtscheller and Da Silva, 1999). The upper panels of Figure 3 show the average ERD/ERS time-courses of channel C3 comparing both recording sessions. Furthermore, we performed a time-frequency analysis of channel C3 using the wavelet-based event-related spectral perturbation (ERSP) technique (Makeig et al., 2004), see Figure 3, middle panels. The lower panel of Figure 3 shows that the power modulations in the respective time-frequency bins are statistically significant across trials ($p<0.05$, FDR-corrected). For ERSP computation we used the epoch [-3 3] seconds with respect to key press. Wavelet parametrization was set to 3 cycles for the lowest frequency (2 Hz) expanding gradually towards half of the number of cycles for the highest frequency (30 Hz). As a result, we observe clear mu-power suppression and traces of beta-power suppression in both datasets. There are two main differences between the two datasets: (1) Motor preparation related ERD onset with respect to the movement onset appeared earlier in the first dataset compared to the second data set. (2) The recovery time (ERS after motor execution) is longer in the second data set (around 1500 ms) compared to the first data set (around 1000 ms). Whether or not these variations result from the different measurement setups or rather the daily constitution of the subject cannot be stated with certainty. In any case, the reduction in mu power derived from signals collected over motor areas that is expected to occur during preparation of movement is visible in both data sets. This observation, together with the practical advantages of the new EEG system described above, validates and supports the use of the new adapted EEG system to assess changes in mu-power ERD/ERS over motor areas.

3.2 Analysis of Patient Data

The same adapted SRTT task was employed to assess, with the adapted device, hand motor-related ERD in adolescents and adults with and without a diagnosis of CP. Example ERD measures are illustrated in Figure 4 for three participants: S25 (upper panel, 13

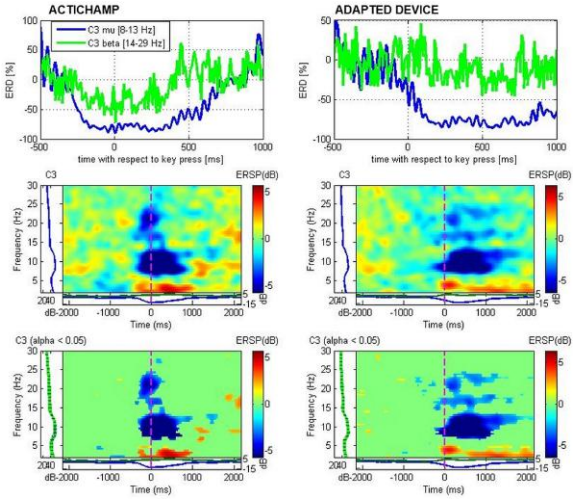

Figure 3: Upper panels: Analysis of mu- and beta-power event-related desynchronization (ERD) in channel C3 according to [2]. Middle panels: Time-frequency representation of channel C3 time-locked to the participant's key press using the wavelet-based event-related spectral perturbation (ERSP) technique. Lower panels: show only those time-frequency bins which were found statistically significant across trials ($p<0.05$, FDR-corrected).

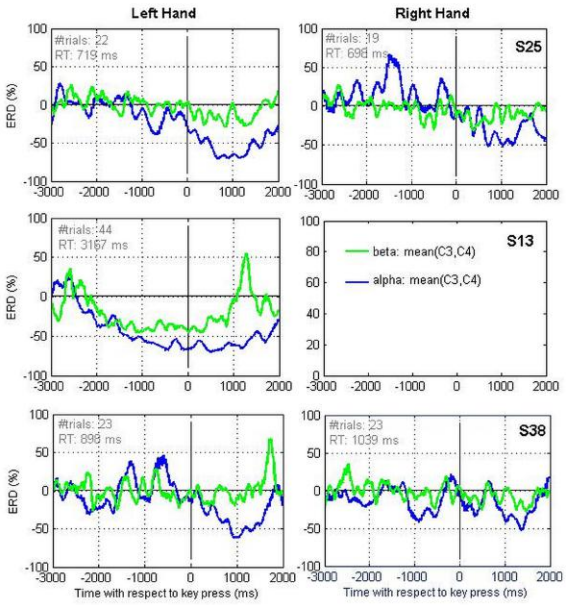

Figure 4: Hand motor-related ERD in three adolescents and adults with and without a diagnosis of CP.

years old, healthy, best hand: right), S13 (middle panel, 45 years, CP with hemiparesis, best hand: left), S38 (lower panel, 15 years old, ataxic CP, best hand: right). Measurements were performed in a normal office at the day rehabilitation centers attended by the patients (participant S25, though not attending any rehabilitation center, was also tested in the same center). ERD is illustrated for both left and right hands, except for participant S13. This patient has a hemiparesis that prevents any movement of the right arm/hand, and therefore he performed the SRTT task with the left hand only. The ERD measures shown were averaged from mu- and beta- bandpass filtered signals recorded from channels C3 and C4. Reductions in mu-power (blue lines) are visible for all cases except for participant S38 with the right hand. Even though signal preprocessing included the removal of epochs containing artifacts (by automatic and visual assessment), these may still have affected the quality of the data and decreased the amount of mu-suppression computed. Participant S38 (middle panel) shows a strong ERD effect, especially for the mu-rhythm. The fact that the reaction time recorded for this participant was much longer than for the other participants (average Reaction Time (RT) of 3167-ms in comparison to 719-ms and 898-ms for participants S25 and S38 respectively) may have facilitated the development of a visible change in mu power with time. It should also be noted that this participant is an adult and that, unlike adolescent participants, was able to remain quiet during the recording. This was observed to be important to increase the number of artifact-free epochs and the probability of capturing a motor-associated suppression of mu power.

3.3 Patient and Experimenter Feedback

The healthy participant tested for the system evaluation described the system as comfortable and not heavy. This initial feedback has been confirmed by the patients and participants of the main experimental study. A short questionnaire has been delivered to some of the participants after the EEG recordings to collect the first impressions on the device. Most patients reported the device to be comfortable (5 out of 5 persons), not heavy (3 out of 5) and not looking harmful or dangerous (5 out of 5). None felt bothered by the system but some were nevertheless aware of it during the recordings (2 out of 5). Researchers on the other hand were very pleased with the easy way the system can be set up and with the short preparation time required, an aspect that they found very helpful when testing all the patients, not only the younger ones.

4 CONCLUSION

Research studies with children, adolescents, with persons having a reduced attention span or with patients receiving medical treatment for long periods of time,

demand a careful planning of the experimental tests. Short experimental testing time, test equipment with non-clinical appearance and/or that does not cause discomfort are relevant factors that influence adherence to participate and can also affect the quality of the data collected. An ease-of-use, unobtrusive EEG device is described in this paper having in view the investigation of motor-related sensorimotor rhythms in patients with cerebral palsy. Commercially available EEG devices have clinical appearance and require long preparation times. Our proposed EEG device addresses these issues. Experimenters reported smooth data collection and overall acceptance of the system among patients. The changes in ERD over time during an adapted SRTT task meet the observations described in the literature (e.g. (Pfurtscheller and Da Silva, 1999)) this way supporting the functionality of our adapted EEG device for the assessment of sensorimotor-related measures of brain activity in patients (adults and adolescents) with sensorimotor disorders of neuronal origin.

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