Ultracompact, EEG-compatible NIRS System

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OBJECTIVE

The development of a miniaturized, portable NIRS system, to be integrated with EEG for BCI applications. Here, we present our most recent step toward this goal, a table-top multi-channel NIRS imager utilizing direct LED illumination and digital signal processing.

INTRODUCTION

Principles of Near-Infrared Spectroscopy (NIRS):

- Uses low-energy optical radiation (~700-900 nm)
- Scatter-dominated light propagation in tissue
- Transmission up to few cm
- Sensitive to absorption changes caused by hemodynamics: measures relative changes in oxygenated and de-oxygenated Hemoglobin (ΔHbO, ΔHbR)
- Requires contact based measurements through 'optodes' (usually fiber optic bundles, sometimes integrated electronic sensors)
- One optode pair (transmitter (source) + receiver (detector)) constitutes one data channel.

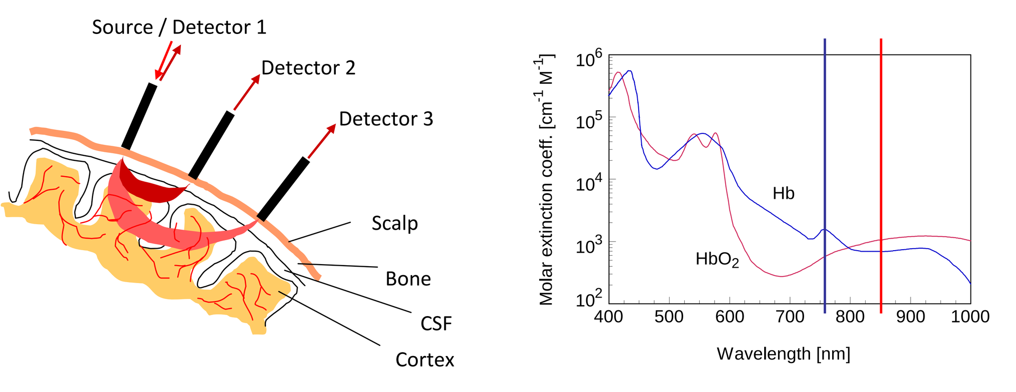

Figure 1. Left: Schematic depiction of NIRS imaging of brain hemodynamics. Right: Spectra of HbO and HbR; vertical lines indicate imaging wavelengths.

NIRS Promises:

- Non-invasive, harmless
- Good time resolution (~10 Hz)
- Can be made small, inexpensive
- Little subject restriction, long term monitoring
- Integrates well with other methods (EEG, MRI,…)

NIRS Challenges:

- Penetration depth ~cm
- Spatial resolution ~mm-cm
- Sensitive to artifacts from motion, surface- near 'global' hemodynamics
- Probe setup

INSTRUMENTATION

- Size: 33 cm (L) × 27 cm (W) × 17 cm (H)
- Mass < 10 kg
- Channels: 1-8 sources, 1-16 detectors
- Scan rate: > 8 Hz (8 sources)
- Illumination: 760/850 nm LED
- Digital signal demodulation

Figure 2. Picture of the instrument. Shown is version with 2 sources, 4 detectors, and 4 trigger connectors for experiment synchronization.

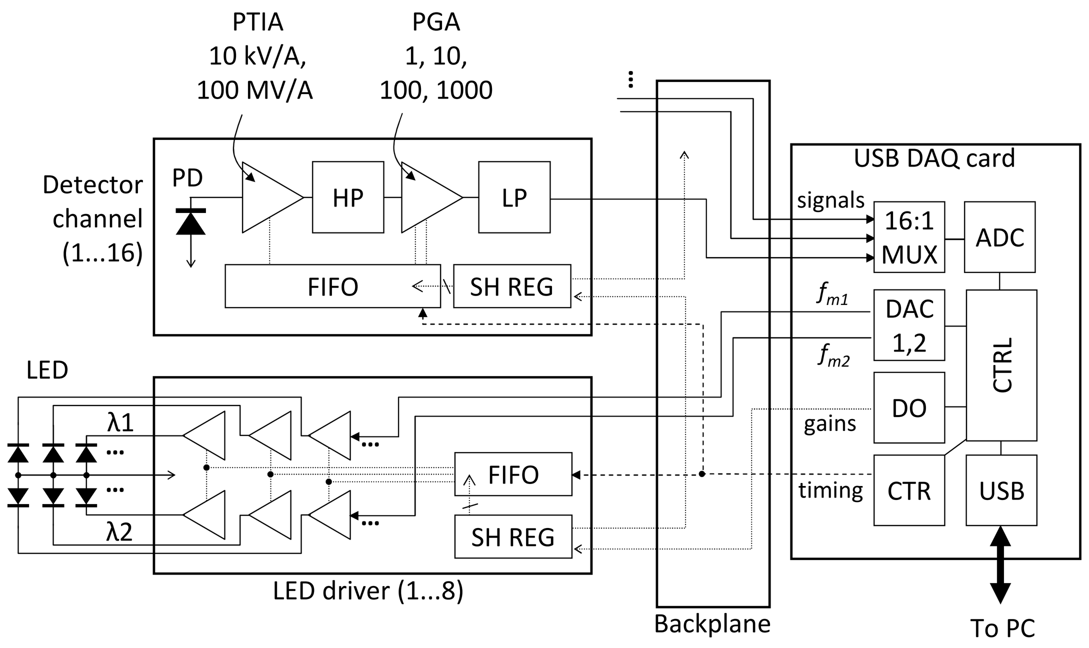

Figure 3. Functional diagram of NIRS imager (omitted: power supply, trigger channels). PD: photo diode; PTIA: programmable transimpedance amplifier; PGA: programmable gain amplifier; HP: RC high-pass filter (f_{3db} = 482 Hz); LP: 4th order Chebyshev low-pass filter (f_{pass} = 2.0 kHz); FIFO: first-in-first-out buffer; SHREG: serial-to-parallel shift register; f_{mod}: modulation frequencies; MUX: multiplexer; ADC: analog-to-digital converter; DAC: digital-to-analog converter; DO: digital out lines; CTR: counter; CTRL: controller.

Illumination

- Time-multiplexed source position encoding
- Simultaneous, frequency-encoded dual-wavelength illumination (760, 850 nm):

$$P_{i,j} = P_{dc} + P_{mod}\sin(2\pi f_{m,i}/f_s\, j + \varphi_i)$$

- Direct tissue contact light emitting diodes (LED)
- 90° Optode head design integrates into EEG electrode
- LEDs vs. Lasers:
    - ~10 mW total optical power per λ @ ~50 mA
    - Spectral width ~30 nm
    - Emission angle (FWHM) ±20°

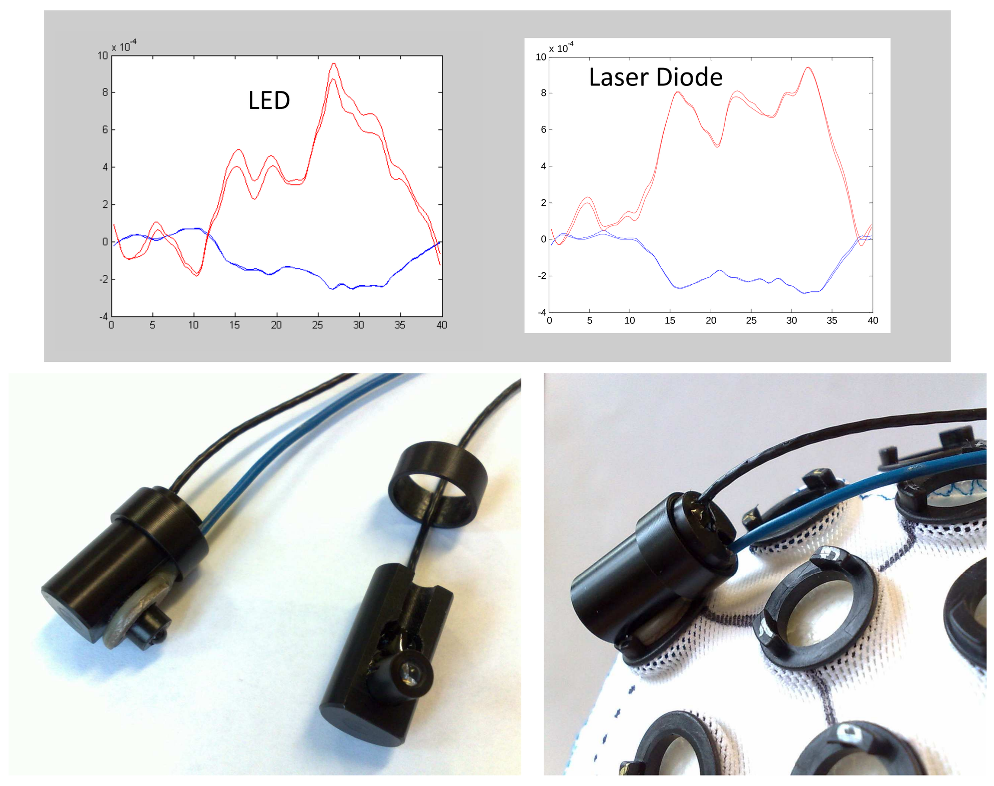

Figure 4. Top row: Hand gripping task result illustrating comparable crosstalk and separability for LED (760/850 nm, left) vs. Laser (760/830 nm, right) illumination. Bottom row: Low-profile LED optodes, from left to right: Connected to ring electrode; optode only with retaining ring; mounted to electrode in EEG cap.

Detection and Signal Processing

- Fiber-optic bundles (∅ = 2.4 mm) with bent tip
- Photo diode in unbiased photovoltaic mode (large dynamic range)
- Gain-switched amplification maximizes dynamic range
- Direct analog-to-digital conversion of modulated signal
- Demodulation in PC software (LabVIEW™) following an algorithm described in [Lasker et al.]:
    1. Component-wise multiplication of signal vector **V** and synthesized orthogonal reference signals $I_{i,j} = \cos(2\pi f_{m,i}/f_s\, j)$ and $Q_{i,j} = \sin(2\pi f_{m,i}/f_s\, j)$:
    $$X'_{i,j} = V_i I_{i,j} \;;\; Y'_{i,j} = V_i Q_{i,j}$$
    2. Time-average the resulting vectors to obtain the in-phase and quadrature amplitudes
    $$X_i = 1/N \textstyle\sum_j^N X_{i,j} \;;\; Y_i = 1/N \sum_j^N Y_{i,j}$$
    3. Compute the magnitude to obtain the detector reading R_d:
    $$R_{d,i} = \mathrm{sqrt}(X_i^2 + Y_i^2)$$
    4. Averaging *exactly* over an interval that is an integer multiple of the modulation period
    $$N = k / f_{m,i} \quad \text{(where } k = 1,2,\ldots)$$
    and using commensurable modulation frequencies results in *perfect* wavelength discrimination.

Noise considerations:

- Detection limit is determined by electronic noise at highest gain
- Dominant noise source is thermal (Johnson) noise of the feedback resistor. Detection bandwidth BW is determined by low-pass RC filter (f_{3dB} = 480 Hz) and anti-aliasing filter (4th order Chebyshev f_{cutoff} = 2.0 kHz):
  BW = 2.0 kHz – 2/π 0.48 kHz = 1.25 kHz
- $V_n = \mathrm{sqrt}(4k_B\, T\, R\, BW)$. For T=300K, R=$10^8$ Ω:
  V_n = 46 μV_{rms}
- Highest gain = 1000 → $V_{n,gain}$ = 46 mV_{rms}
- Averaging over 100 samples reduces noise by factor 10 → $V_{n,demod}$ = 4.6 mV_{rms} (Measured: V_n = 5 mV_{rms})
- Noise equivalent power (NEP): $V_{sig} = V_{noise}$ = 5 mV_{rms}
  → $V_p = \sqrt{2}\, V_{rms}$ = 7 mV_p → $I_p = V_p$ / 10^{11} Ω = 7×10^{-14} A → NEP = 2W/A × I_p = 0.14 pW_p

RESULTS

Instrument Performance

- Sensitivity: better 0,5 pW NEP
- Stability: better 0.01%
- Drift: < 1%/hr after warm up
- Dynamic range (theo):
  [1 V / 10^4 V/A] / [5 mV / 10^{11} V/A] = 2×10^9 = 93 dB_{pwr}

Simultaneous NIRS-EEG validation

Paradigm:

- Alternating self-paced, visually cued finger tapping
- Left (20 s) → rest (20 s) → right (20 s) → rest (20 s)… [9 times]

NIRS measurement:

- 2 Sources, 4 Detectors (per hemisphere: 1 S x 2 D), f_{sample} = 22.5 Hz
- Customized EEG cap (EASYCAP GmbH) for electrode/optode placement (Fig. 5)
- Signal analysis in MATLAB™ based NILAB (Charite Berlin): Band pass filter, modified Beer-Lambert law, block-averaging

EEG measurement:

- 13-channel recording with BrainAmp (Brain Products GmbH): f_{sample} = 1.0 kHz, FCz as reference, BW = DC to 250 Hz
- Band pass filter [0.5 Hz, 100Hz], epoched for each condition (-3 s to +25 s relative to stimulus onset)
- Wavelet-based time-frequency (TF) analysis (Morlet, 12 cycles, 5-25 Hz) on single trial basis
- Averaging of single trial TF results; baseline (-1 to 0 s) subtraction

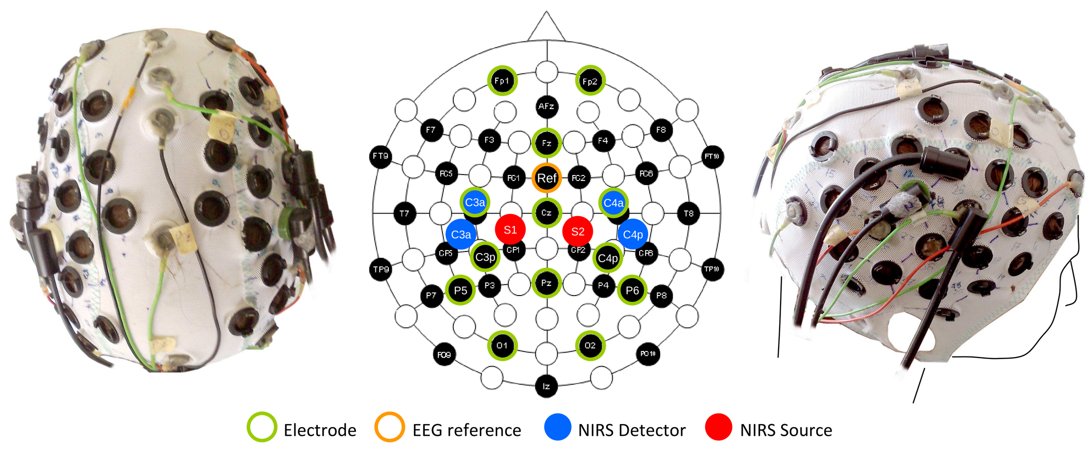

Figure 5. Electrode and optode placement on EEG cap.

Experimental Results

EEG

- No spectral interferences from LED optode
- Sustained μ-desynch (α- & β-range) during contralateral tap

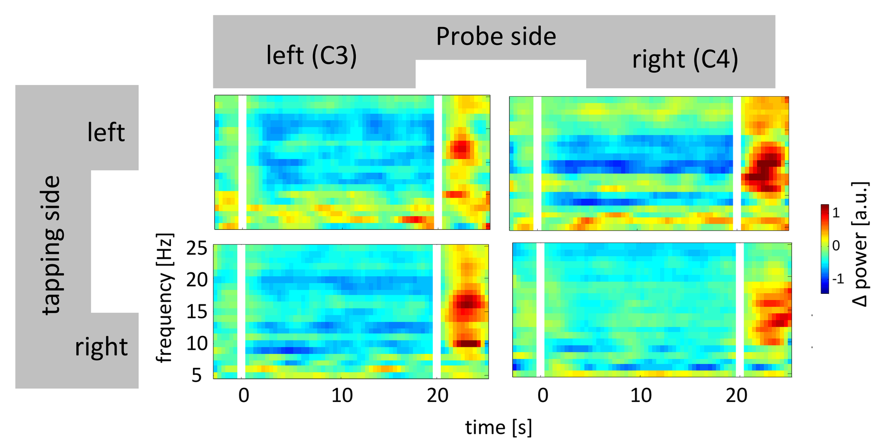

Figure 6. EEG time-frequency results.

NIRS

- Prototypical activation for motor task is observed: HbO↑ & HbR ↓; sustained response to tapping
- HbO: Susceptible to physiological noise, therefore less indicative for tapping side
- HbR: Stronger decrease contralateral to tapping side
- Robust, condition related single-trial response

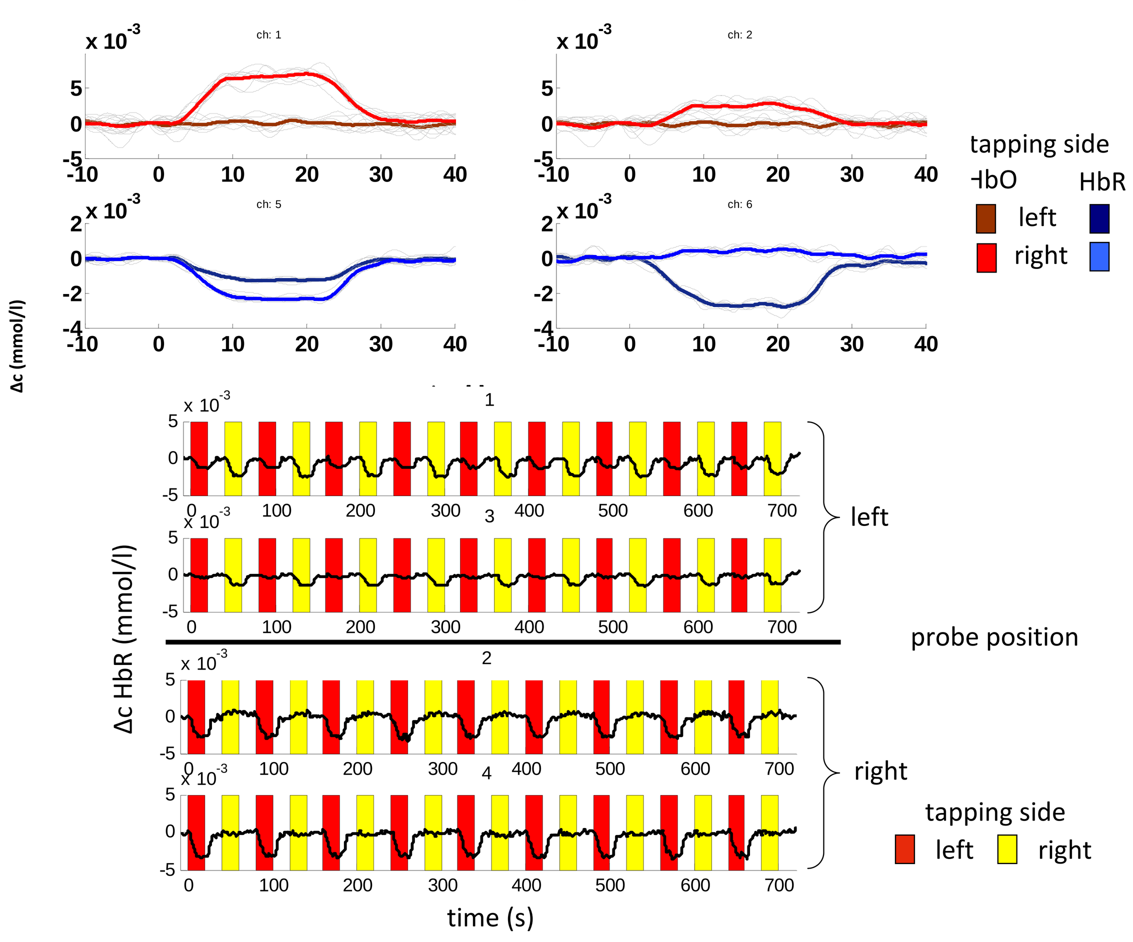

Figure 7. NIRS results. Top: Block-averaged vs. single-trial response. Bottom: Continuous time courses for nine consecutive trials.

DISCUSSION

- No interferences in EEG signals
- Excellent signal-to noise ratio in HbO and HbR
- Fast and flexible probe placement for concurrent EEG/NIRS measurement
- Robustness of single trial response promising for real-time applications (BCI, neuro-feedback)
- Portability/compactness allows field studies

Abbreviations: HbO: oxy-hemoglobin; HbR: deoxy-hemoglobin; LED: light emitting diode; *P*: power; *fm*: modulation frequency; *i*: wavelength index; *j*: sample index; λ: wavelength; **V**: measured discrete signal vector; $\mathbf{I}_i$,$\mathbf{Q}_i$: discrete in-phase and out-of phase reference vectors; X_i,Y_i: in-phase and out-of phase amplitudes; $R_{d,i}$: detector reading; *fs*: sampling frequency; BW: bandwidth; k_B: Boltzmann's constant; *R*: resistance; *V*: voltage; *I*: current;

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