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14. ABSTRACT
This study aims to design, develop, and test a portable, lightweight, noninvasive neuroimaging system that supports simultaneous electroencephalogram (EEG) and functional NIR spectroscopic (fNIRS) acquisition for biological or cognitive neuroscience studies in operational environments. The system features novel EEG/NIRS electrodes, known as electro-opodes, and miniaturized supporting hardware/software. In the past few years, our team, composed of faculty, postdoctoral fellows and graduate students, has designed and developed dry EEG and fNIR

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EEG, fNIR, wearable system

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Report Title

CONCURRENT EEG AND NIRS TOMOGRAPHIC IMAGING BASED ON WEARABLE ELECTRO-OPTODES

ABSTRACT

This study aims to design, develop, and test a portable, lightweight, noninvasive neuroimaging system that supports simultaneous electroencephalogram (EEG) and functional NIR spectroscopic (fNIRS) acquisition for biological or cognitive neuroscience studies in operational environments. The system features novel EEG/NIRS electrodes, known as electro-opodes, and miniaturized supporting hardware/software. In the past few years, our team, composed of faculty, postdoctoral fellows and graduate students, has designed and developed dry EEG and fNIR sensors that allow non-invasive and non-intrusive acquisition of EEG and fNIR signals. We have also designed the form factor of Electro-optodes that integrates the EEG and fNIR sensors in an elastic cap. We further evaluated the quality of EEG signals acquired by the dry spring-loaded EEG sensors and fNIR sensors through three experiments. This study has also made a lot of progress in designing and developing a data-acquisition VLSI chip that can acquire, amplify, digitize and process EEG and NIRS data. Lastly, to improve the fidelity of the EEG recordings, we have developed and implemented real-time artifact correction algorithms, Artifact Subspace Reconstruction, for online and real-time rejection of artifacts that often contaminate EEG signals recorded in real-world environments.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u> <u>Paper</u>

04/13/2014 19.00 Chun-Ling Lin, Fu-Zen Shaw, Kuu-Young Young, Chin-Teng Lin, Tzyy-Ping Jung. EEG Correlates of Haptic Feedback in a Visuomotor Tracking Task,
NeuroImage, (02 2012): 2258. doi:

04/13/2014 20.00 Yijun Wang, Yu-Te Wang, Tzyy-Ping Jung. Translation of EEG Spatial Filters from Resting to Motor Imagery Using Independent Component Analysis,
PLoS ONE, (05 2012): 0. doi:

04/13/2014 21.00 Lun-De Liao, Chin-Teng Lin, K. McDowell, A. E. Wickenden, K. Gramann, Tzyy-Ping Jung, Li-Wei Ko, Jyh-Yeong Chang. Biosensor Technologies for Augmented Brain–Computer Interfaces in the Next Decades,
Proceedings of the IEEE, (05 2012): 1553. doi: 10.1109/JPROC.2012.2184829

04/13/2014 22.00 Zhilin Zhang, Tzyy-Ping Jung, Scott Makeig, Bhaskar D. Rao. Compressed Sensing of EEG for Wireless Telemonitoring With Low Energy Consumption and Inexpensive Hardware,
IEEE Transactions on Biomedical Engineering, (01 2013): 221. doi: 10.1109/TBME.2012.2217959

04/13/2014 23.00 Shao-Wei Lu, W. David Hairston, Shih-Yu Li, Kaleb Mcdowell, Chin-Teng Lin, Kelvin S. Oie, Tzyy-Ping Jung, Stephen Gordon, Keith W. Whitaker. Real-World Neuroimaging Technologies,
IEEE Access , (05 2013): 131. doi: 10.1109/ACCESS.2013.2260791

09/14/2011 8.00 Yu-Te Wang, Yijun Wang, Tzyy-Ping Jung. A cell-phone-based brain–computer interface for communication in daily life,
Journal of Neural Engineering, (04 2011): 0. doi: 10.1088/1741-2560/8/2/025018

09/20/2012 9.00 Yu Mike Chi, Yu-Te Wang, Yijun Wang, Christoph Maier, Tzyy-Ping Jung, Gert Cauwenberghs. Dry and Non-contact EEG Sensors for Mobile Brain-Computer Interfaces,
IEEE Transactions on Neural Systems and Rehabilitation Engineering, (03 2012): 228. doi:

09/20/2012 11.00 Shang-Wen Chuang, Li-Wei Ko, Yuan-Pin Lin, Ruey-Song Huang, Tzyy-Ping Jung, Chin-Teng Lin. Co-modulatory spectral changes in independent brain processes are correlated with task performance,
NeuroImage, (09 2012): 1469. doi: 10.1016/j.neuroimage.2012.05.035

09/20/2012 10.00 Yijun Wang, Yu-Te Wang, Tzyy-Ping Jung, Pedro Antonio Valdes-Sosa. Translation of EEG Spatial Filters from Resting to Motor Imagery Using Independent Component Analysis,
PLoS ONE, (05 2012): 0. doi: 10.1371/journal.pone.0037665

09/20/2012 12.00 Chun-Ling Lin, Fu-Zen Shaw, Kuu-Young Young, Chin-Teng Lin, Tzyy-Ping Jung. EEG correlates of haptic feedback in a visuomotor tracking task,
NeuroImage, (05 2012): 2258. doi: 10.1016/j.neuroimage.2012.02.008

09/20/2012 13.00 Y. M. Chi, Yu-Te Wang, Yijun Wang, C. Maier, Tzyy-Ping Jung, G. Cauwenberghs. Dry and Noncontact EEG Sensors for Mobile Brain–Computer Interfaces,
IEEE Transactions on Neural Systems and Rehabilitation Engineering, (03 2012): 228. doi: 10.1109/TNSRE.2011.2174652

TOTAL: **11**

Number of Papers published in peer-reviewed journals:

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Received Paper

TOTAL:

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(c) Presentations

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/29/2011	5.00	Yu-Te Wang, Yu M. Chi, Yijun Wang, Christoph Maier, Gert Cauwenberghs, Tzyy-Ping Jung. Dry Contact and Non-contact EEG Sensors for Mobile Wireless Brain-Computer Interfaces, Annual Meeting of Society for Neuroscience. 12-NOV-11, . : ,

TOTAL: **1**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
04/13/2014	24.00	Yu-Te Wang, Yijun Wang, Chung-Kuan Cheng, Tzyy-Ping Jung. Measuring Steady-State Visual Evoked Potentials from non-hair-bearing areas, 2012 34th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). 27-AUG-12, San Diego, CA, USA. : ,
04/13/2014	25.00	Kuan-Chih Huang, Tzyy-Ping Jung, Chun-Hsiang Chuang, Li-Wei Ko, Chin-Teng Lin. Preventing lapse in performance using a drowsiness monitoring and management system, 2012 34th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). 27-AUG-12, San Diego, CA, USA. : ,
04/13/2014	26.00	Tim Mullen, Christian Kothe, Yu Mike Chi, Alejandro Ojeda, Trevor Kerth, Scott Makeig, Gert Cauwenberghs, Tzyy-Ping Jung. Real-time modeling and 3D visualization of source dynamics and connectivity using wearable EEG, 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). 02-JUL-13, Osaka, Japan. : ,
04/13/2014	27.00	Bret Kellihan, Tracy Jill Doty, W. David Hairston, Jonroy Canady, Keith W. Whitaker, Chin-Teng Lin, Tzyy-Ping Jung, Kaleb McDowell. A Real-World Neuroimaging System to Evaluate Stress, The 15th International Conference on Human-Computer Interaction. 21-JUL-13, . : ,
08/29/2011	4.00	Yu-Te Wang, Yijun Wang, Tzyy-Ping Jung. A Cell-Phone Based Brain-Computer Interface for Communication in Daily Life, International Conference on Artificial Intelligence and Computational Intelligence (AICI'10). 23-OCT-10, . : ,
08/30/2011	6.00	Yu-Chieh Huang, Ching-Kun Chen, Mang Ou-Yang, Jin-Chern Chiou, Jeng-Ren Duann. A Novel 8-channel System for Photoplethysmography (PPG) and Regional Cerebral Oxygen Saturation (rSO2) Monitoring on Brain, The 2011 Symposium on Engineering, Medicine and Biology Applications. 08-JUL-11, . : ,
09/20/2012	15.00	MUhammad Tahir Akhtar, Tzyy-Ping Jung, Scott Makeig, Gert Cauwenberghs. Recursive independent component analysis for online blind source separation, 2012 IEEE International Symposium on Circuits and Systems - ISCAS 2012. 19-MAY-12, Seoul, Korea (South). : ,
09/20/2012	16.00	Kuan-Chih Huang, Tzyy-Ping Jung , Chun-Hsiang Chuang, Li-Wei Ko, Chin-Teng Lin. Preventing Lapse in Performance Using a Drowsiness Monitoring and Management System, The 34th Annual International Conference of the IEEE EMBS. 28-AUG-12, . : ,
09/20/2012	17.00	Yu-Te Wang, Yijun Wang, Chung-Kuan Cheng, Tzyy-Ping Jung. Measuring Steady-State Visual Evoked Potentials fromNon-hair-bearing Areas, The 34th Annual International Conference of the IEEE EMBS. 28-AUG-12, . : ,
09/20/2012	18.00	Junhua Li, Yijun Wang, Liqing Zhang, Tzyy-Ping Jung. Combining ERPs and EEG Spectral Features for Decoding Intended Movement Direction, The 34th Annual International Conference of the IEEE EMBS. 27-AUG-12, . : ,

TOTAL: **10**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/29/2011	3.00	YU M. Chi, Yu-Te Wang, Yijun Wang, Christoph Maier, Tzyy-Ping Jung, Gert Cauwenberghs. Dry and Non-contact EEG Sensors for Mobile Brain-Computer Interfaces, (08 2011)
09/02/2011	7.00	Chih-Wei Chang, Chia-Lin Chang, Ching-Hsing Luo, Jin-Chern Chiou . A Stacked Multichip Sensing Interface for Implantable Three Dimensional Neural Recording Applications, IEEE Journal on Emerging and Selected Topicsin Circuits and Systems (09 2011)
TOTAL:		**2**

Number of Manuscripts:

Books

Received		Paper
09/20/2012	14.00	Yijun Wang, Tzyy-Ping Jung. Improving Brain–Computer Interfaces Using Independent Component Analysis, Berlin, Germany: Springer-Verlag Berlin Heidelberg, (03 2012)
TOTAL:		**1**

Patents Submitted

Patents Awarded

Awards

Outstanding Alumnus Award, National Chiao-Tung University, Hsinchu, Taiwan, 2012.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Chiou, Jien-Haw	0.50	
Yeh, Wei-Ling	0.50	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Tzyy-Ping Jung	0.05	
Jeng-Ren Duann	0.50	
FTE Equivalent:	**0.55**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Yeh, Wei-Ling	
Chiou, Jien-Haw	
Total Number:	**2**

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment.

Technology Transfer

Final Report

DATE: **SEP. 1, 2009 – AUG. 31, 2013**

TO: Dr. Liyi Dai, Ph.D., Army Research Office

FROM: JENG-REN DUANN AND TZYY-PING JUNG

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ENTITY: UNIVERSITY OF CALIFORNIA SAN DIEGO, CA

SUBJECT: FINAL REPORT FOR WORK PERIOD (SEP. 1, 2009 – AUG. 31, 2013)

PROJECT TITLE: CONCURRENT EEG AND NIRS TOMOGRAPHIC IMAGING BASED ON WEARABLE ELECTRO-OPTODES

Distribution List and Addresses

One report to:

Dr. Liyi Dai, Ph.D, Army Research Office

Abstract

This study aims to design, develop, and test a portable, lightweight, noninvasive neuroimaging system that supports simultaneous electroencephalogram (EEG) and functional NIR spectroscopic (fNIRS) acquisition for biological or cognitive neuroscience studies in operational environments. The system features novel EEG/NIRS electrodes, known as electro-opodes, and miniaturized supporting hardware/software. In the past few years, our team, composed of faculty, postdoctoral fellows and graduate students, has designed and developed dry EEG and fNIR sensors that allow non-invasive and non-intrusive acquisition of EEG and fNIR signals. We have also designed the form factor of Electro-optodes that integrates the EEG and fNIR sensors in an elastic cap. We further evaluated the quality of EEG signals acquired by the dry spring-loaded EEG sensors and fNIR sensors through three experiments. This study has also made a lot of progress in designing and developing a data-acquisition VLSI chip that can acquire, amplify, digitize and process EEG and NIRS data. Lastly, to improve the fidelity of the EEG recordings, we have developed and implemented real-time artifact correction algorithms, Artifact Subspace Reconstruction, for online and real-time rejection of artifacts that often contaminate EEG signals recorded in real-world environments.

Objective

This study aims to design, fabricate, and test a truly portable, lightweight, noninvasive, neuroimaging system that supports simultaneous electroencephalogram (EEG) and functional Near Infrared Spectroscopic (fNIRS) acquisition to provide complementary information of the brain. The acquired neural dynamics could be comparable to those obtained from simultaneous EEG and functional Magnetic Resonance Imaging (fMRI) recordings. The envisioned dual-modality neuroimaging system will feature our newly developed EEG/NIRS electrodes, known as electro-optodes, based on Micro-Electro-Mechanical System (MEMS) technology and miniaturized supporting hardware and software for biological or cognitive monitoring of participants in operational environments. Another major goal of this project is to develop advanced signal-processing methods and software for (1) increasing signal-to-noise ratio of the acquired EEG and optical imaging, (2) 2-D and 3-D image reconstruction and rendering to reconstruct the optical images for investigating neurovascular coupling with minimum inter-modality interferences and preparation demands.

Scientific Barriers

The advantages of simultaneous EEG/fMRI recordings have been explored by many studies and received increasing attention in neuroscience community [Ives et al. (1993); Huang-Hellinger et al. 1995; Lemieux et al., 1997]. However, simultaneous EEG/fMRI recordings have formidable technical problems. For example, in EEG/fMRI recording, any ferromagnetism in the scanner can be dangerous for the subject, and will certainly cause unacceptable loss in the BOLD image. Then, small movements of the electrodes or cables in a strong magnetic field will introduce artifactual currents. The recorded EEG signals will be completely useless before the MR artifacts can be removed. To remove the MR-induced artifacts, the onset timings and the waveforms of the MR artifacts need to be precisely registered during the acquisition of each MR image slice. This, in turn, requires high sampling rate for EEG recordings (at least 5 KHz compared with 250 Hz for regular EEG recordings). On the other hand, EEG electrodes may also introduce deformation of the magnetic field of the MR scanner and in turn cause signal void in (f)MR images around the scalp electrodes. All these interferences make simultaneous EEG/fMRI and post-processing extremely difficult. Therefore, a truly small, lightweight, battery-powered EEG/fMRI system for concurrent EEG/fMRI recordings of the freely-moving subjects in real-world environments will be extremely difficult, if ever possible, in the near future.

Significance

This study is integrating a novel EEG/fNIRS electro-optodes that can be used as an EEG electrode and a NIR light emitter and photo detector, supporting wearable data acquisition (DAQ), signal-processing and image rendering software into a wearable neuroimaging system. We will also develop advanced 2-D and 3-D image reconstruction algorithms to reconstruct the optical images from the recorded fNIRS signals. The envisioned simultaneous EEG/fNIRS acquisition system is completely novel and different from any other currently available systems. First, the envisioned system features brand new dry EEG/NIRS electro-optodes, which can function as an NIR emitter, detector, and an EEG electrode without requiring any skin preparation and conductive paste. Most importantly, the electro-optodes also comprises built-in NIR light sources and NIR waveguide to bypass the high reflectance of the human dead-skin layer such that low-power NIR light sources will be sufficient for high-quality recording. In addition to the innovative hardware design, fabrication, and integration, ICA-based signal processing can separate the mixture signals caused by multiple light sources and multiple possible pathways. As a result, we are able to reconstruct a 3-D optical tomography, which may be more specific to the underlying BOLD effects. In turn, we should be able to better assess the inter-relationship between the BOLD effects and the neural activities measured by the simultaneously recorded EEG signals.

Why is this research of value to the Army?

Given the increased operation tempo and complexity that soldiers are facing today and in the future, new approaches and technologies will be needed to maximize and maintain attentional capacity. Understanding how this complexity affects human sensory, perception, and cognitive performance to effectively exploit the cognitive capabilities of individuals is thus very crucial to improve and optimize individual or team performance in military environments. Monitoring the neurophysiological activity of Soldiers within a complex environment, however, poses severe measurement challenges to the current laboratory-oriented sensing technology. Successful development of a multi-modality neuroimaging system could allow assessment of individual neurocognitive performance in military environments and could also play important roles in enhancing individual and team learning during military training.

Accomplishments

During the past few years, we have (1) combined dry EEG electrode and NIRS probe into one integrated electro-optode for simultaneously EEG and fNIRS recording; (2) developed a VLSI neuroimaging chip for data acquisition; (3) conducted three experiments to validate the feasibility of the custom-made fNIR probe; and (4) developed online automatic artifact removal approach to improve the fidelity of the EEG recordings. The details of the achievements are itemized below:

1. Integrated Dry EEG Electrode and NIRS Probe into an Electro-optode for simultaneous EEG and fNIR recording

The main purpose of this project is to develop an electro-optode that combines the capability of simultaneously recording both EEG and fNIRS signals from the same site by integrating both EEG electrode and NIR probe into one electro-optode. Figure 1 shows the design of the electro-optode on a PCB with C-shaped design to record signals from heir-bearing sites. Such a design has proved capable of placing the IR/Red LEDS and photodiodes more closely to the scalp without the interference from the hair. We have also conducted experiments to test the feasibility of such an integrated electro-optode by examining the quality of the acquired fNIRS and EEG signals.

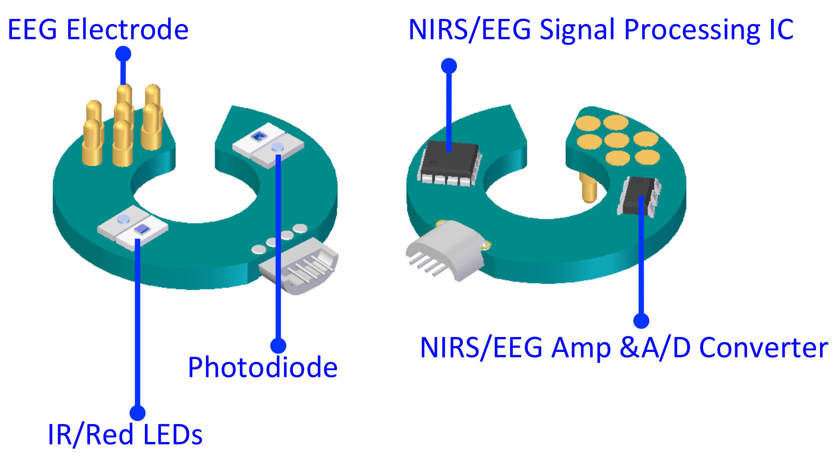


Figure 1. The integration of dry EEG electrode and NIRS probe to form a electro-optode for simultaneous EEG and fNIR recordings.

2. A VLSI Neuroimaging Chip

To acquire EEG and fNIR data measured by the Electro-Optodes, we have designed and fabricated a single neuroimaging chip featuring an analog front-end, analog-to-digital converter (ADC) and digital signal processing (DSP) units. The architecture of the neuroimaging chip is shown in Figure 2. We are currently testing the functionality of the VLSI chip.

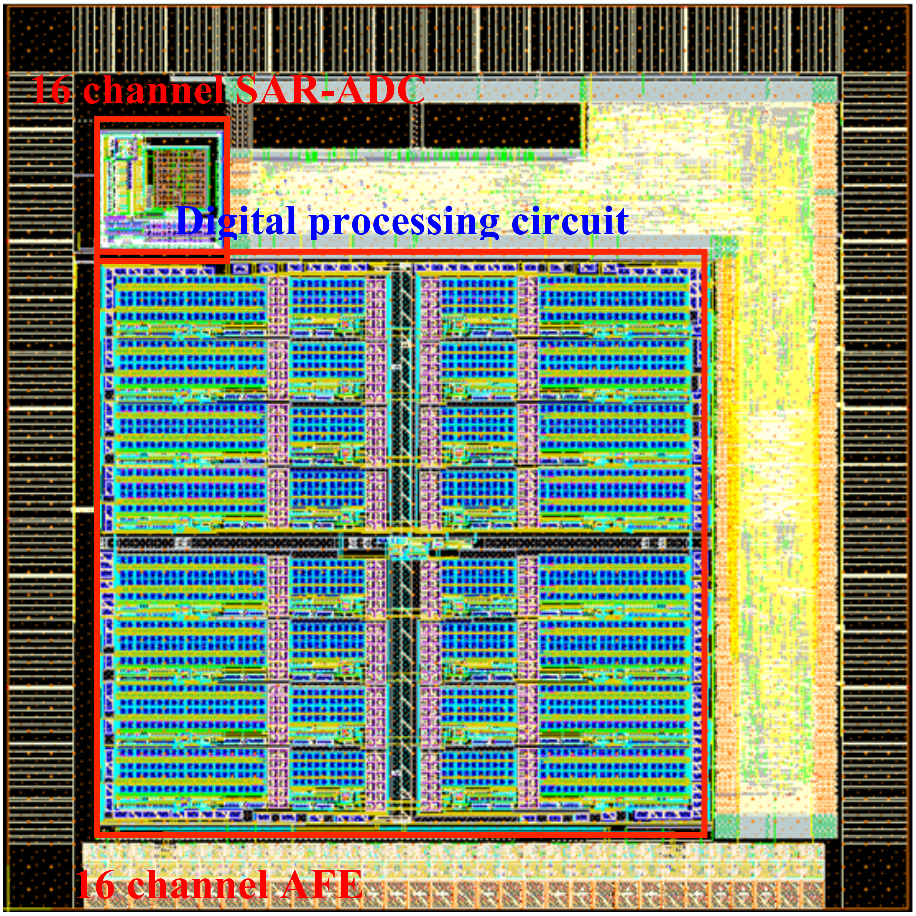


Figure 2. The architecture of a neuroimaging chip.

The specification of the proposed is shown in Table 1.

Table 1. The specification of the rehabilitation chip

Item	Specification
CMOS Technology	0.18 um
Die size	2.5x2.5mm^2
Operation voltage	1.8V
Clock rate	66MHz
Power consumption	96mW(Digital)

3. Three Experiments to Validate the Custom-made NIRS Probes

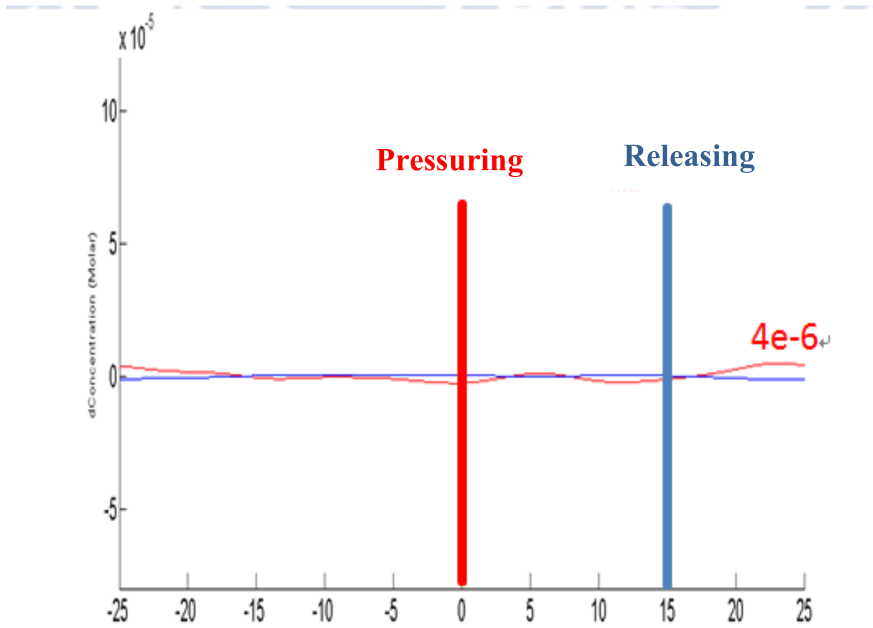
Therefore, we had conducted a series of experiments to test the feasibility by checking not only the signal quality but also the derived hemodynamic responses from the recorded signals. These experiments included (1) a vascular occlusion test on the forearm regions of human subjects, (2) a breath holding test on the human subjects, and (3) an fNIR experiment during a mental arithmetic task. The detail experimental paradigms and the results are itemized below.

3.1 A Vascular Occlusion Test on the Forearm Regions of Human Subjects

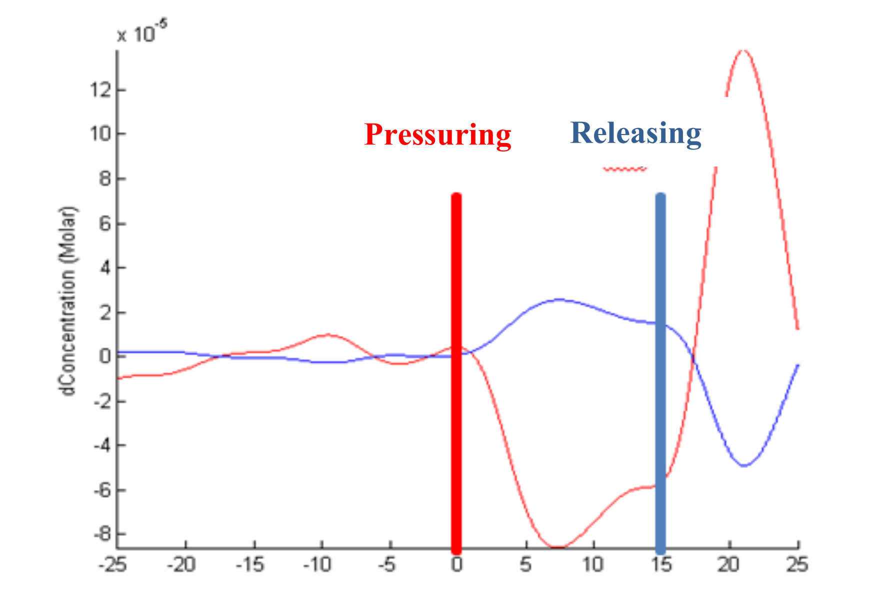
To verify the NIRS system and the algorithm, we assess the variations of the concentration of oxyhemoglobin ([HbO_2]) and deoxyhemoglobin ([Hb]) when external force was applied to the forearm to block the blood flow. Figure 3 shows the experimental setup. The NIRS probe including a PD and an LED was placed on the left forearm of the subject, and the cuff was normally placed smoothly and snugly around the upper arm. In the experiment, the blood pressure was increased to 220 mmHg and held by an inflatable cuff of a sphygmomanometer, and then released the cuff after 15 seconds. The concentration of [HbO_2] and [Hb] were compared across the three conditions (i.e. pre-occlusion, occlusion, and post-occlusion) to assess the functionality of the proposed NIRS probe.

Figure 3. Experimental setup of an inflatable cuff and the NIRS probe.

Figure 4 shows the changes of [Hb] and [HbO_2] with and without external pressure of the inflatable cuff. The red bold line at 0 sec represents the time point of adding external pressure to increase and hold the blood pressure at 220 mmHg. The bold blue line shows the cuff releases 15 seconds later. The red and the blue traces depict the concentrations of [HbO_2] and [Hb], respectively. Figure 4(a) is the control condition without external pressure. Figure 4(b) shows the changes with pressured and unpressured cuff. Apparently, when the blood pressure increased, the [HbO_2] of forearm decreased and the [Hb] increased considerably.



(a)



(b)

Figure 4. (a) changes of [Hb] and [HbO_2] without external pressure; (b) changes of [Hb] and [HbO_2] with external pressure.

3.2 Breath-Holding Experiment on the Humans Brains

Having validated the concentrations of [Hb] and [HbO_2] in the forearm vascular occlusion experiment, we conducted a breath-holding experiment to further verify the proposed NIRS system for the brain. The breath-holding experiments were introduced to control the concentration of oxygen in the brain. In the experiments, the NIRS probes were placed at Fp1, as shown in Figure 5.

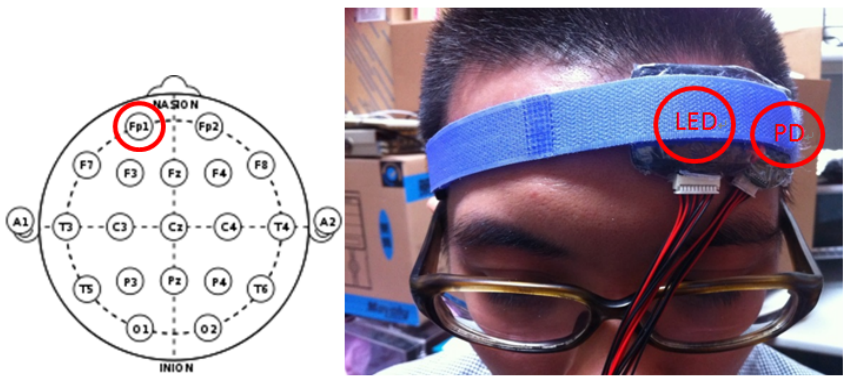


Figure 5. The NIRS probe was placed at Fp1 in the breath-holding experiments.

Figure 6 shows the experimental procedure. The first 30 seconds is a pre-rest (control) stage. After the pre-rest stage, subjects should start to exhale all of the air out of their lung in 2 seconds for creating the condition of ischemia and then hold breath for the next 28 seconds. After the breath-holding stage, the subject can breathe normally for 30 seconds until the next trial begins. Each subject repeated the experimental for 10 times in one session to derive an averages hemodynamic response of the breath-holding experiment.

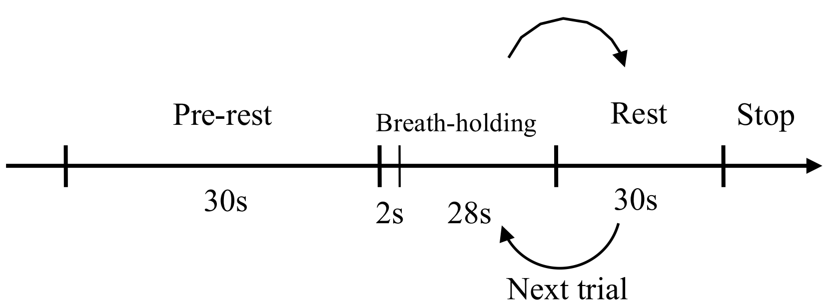
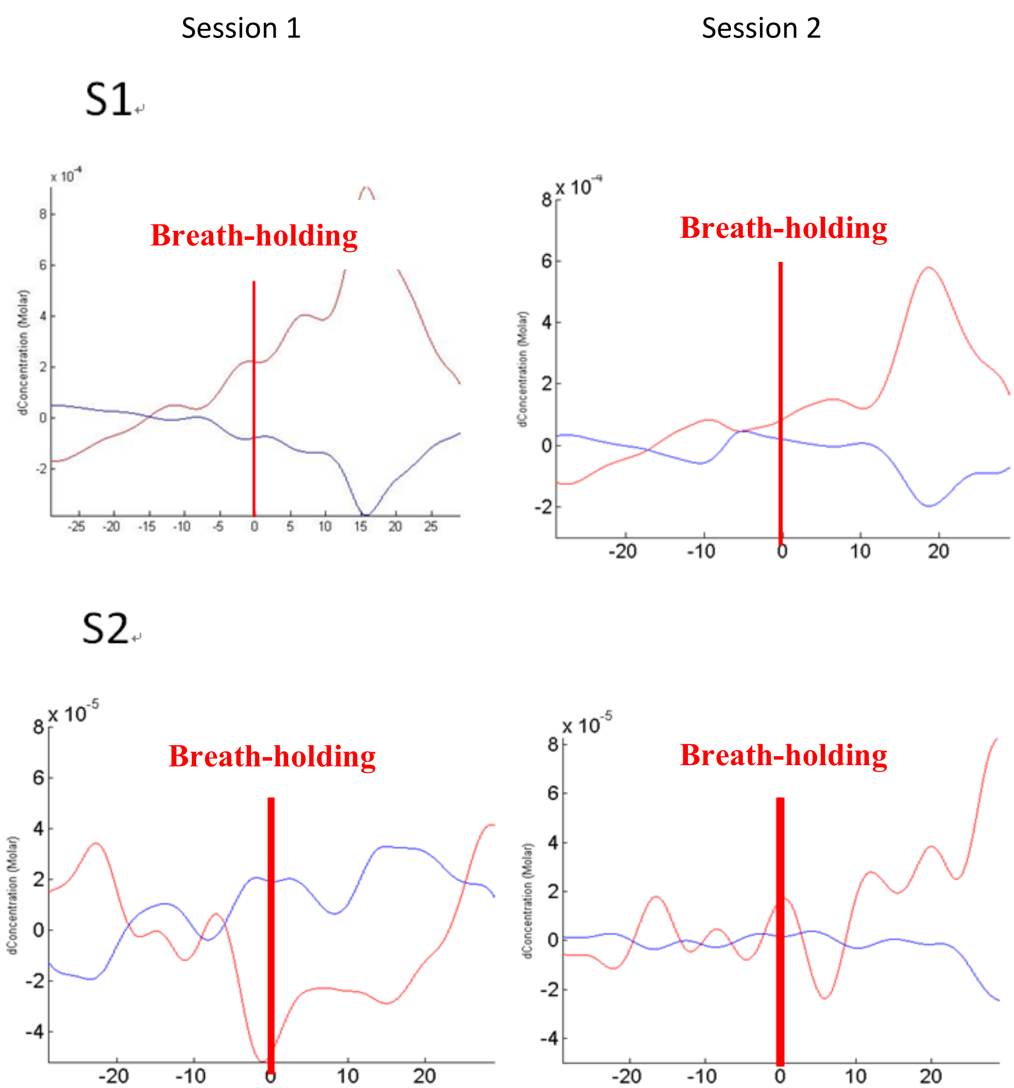


Figure 6. The timeline of the breath holding experiment.

Four subjects (S1, S2, S3 and S4) participated in the breath-holding experiments, each participated in two sessions. Figure 7 shows the empirical results of [Hb] and [HbO_2]. The bold red line represents the onset of breath-holding after 30-second pre-rest stage. The results shows that the [HbO_2] and [Hb] would increase and decrease, respectively. This phenomena may be because there is a protective mechanism to deliver oxygen to the brain when the oxygen concentration is insufficient, and then the [HbO_2] of subjects would increase for protection.



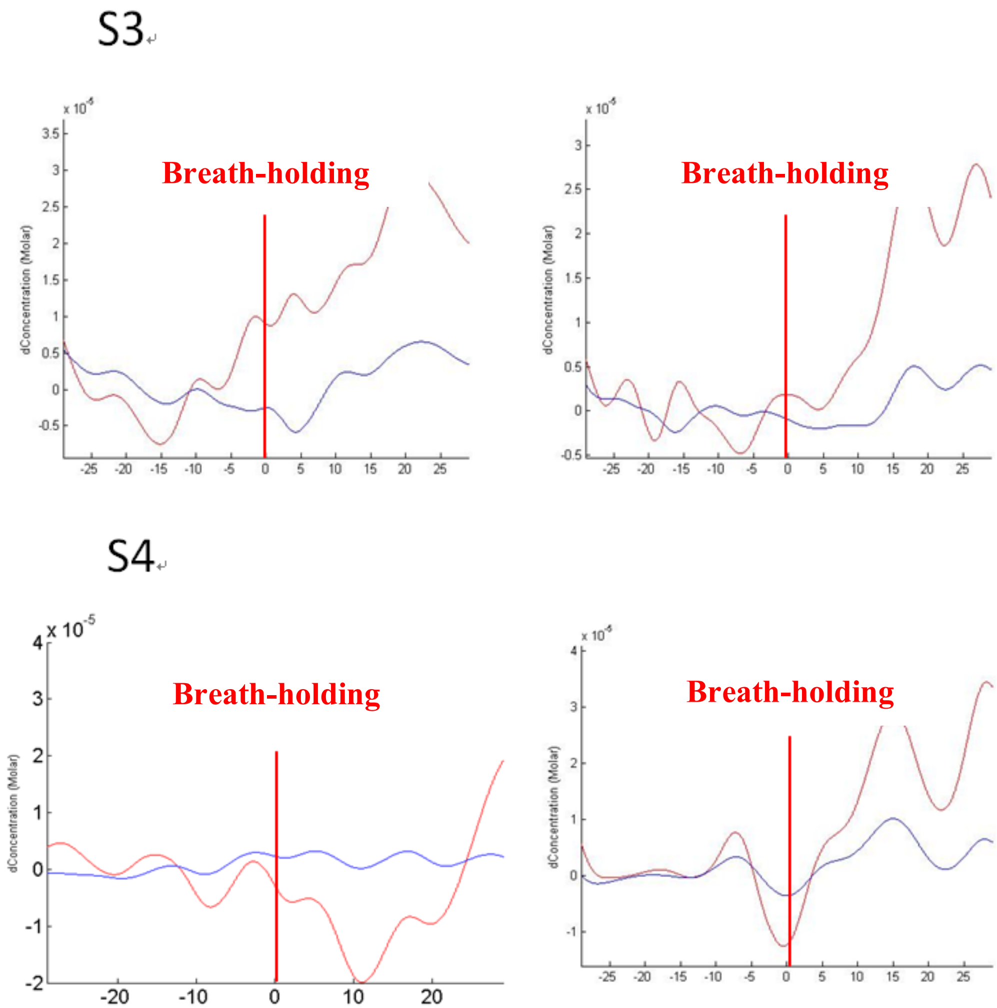


Figure 7. The results of breath-holding experiments from 4 subjects, each performed two sessions.

3.3 fNIR Experiment with a Mental Arithmetic Task

Sections 2.1 and 2.2 show the changes of [HbO_2] and [Hb] in a large area for more critical conditions, such as vascular occlusion and breath holding. Such critical conditions might create more noticeable hemodynamic changes. To evaluate the feasibility of the proposed NIRS system for assessing brain activity, we then conducted a more realistic experiment, as we would normally do during a cognitive task. This study tested the hemodynamic responses over the forehead regions during a mental arithmetic task. Figure 8 shows the test procedure. Each trial started with a 30-second pre-rest stage, then the subjects performed a 15-second mental arithmetic test (two-digit to two-digit addition), followed by a 15-second rest stage as the control. The subjects repeated the procedure 10 times to derive the averaged hemodynamic responses. Each subject participated in two sessions on separate occasions that were two weeks apart.

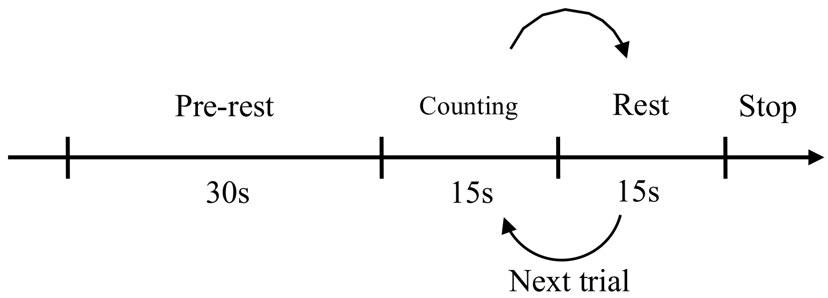


Figure 8. The procedure of the mental arithmetic experiments

Figure 9 shows the averaged changes of $[HbO_2]$ and [Hb] across 10 trials from two subjects. The [HbO2] increases the [Hb] decreased once the subjects started counting indicating the subjects' brain consumed more oxygen to support the mental arithmetic operations.

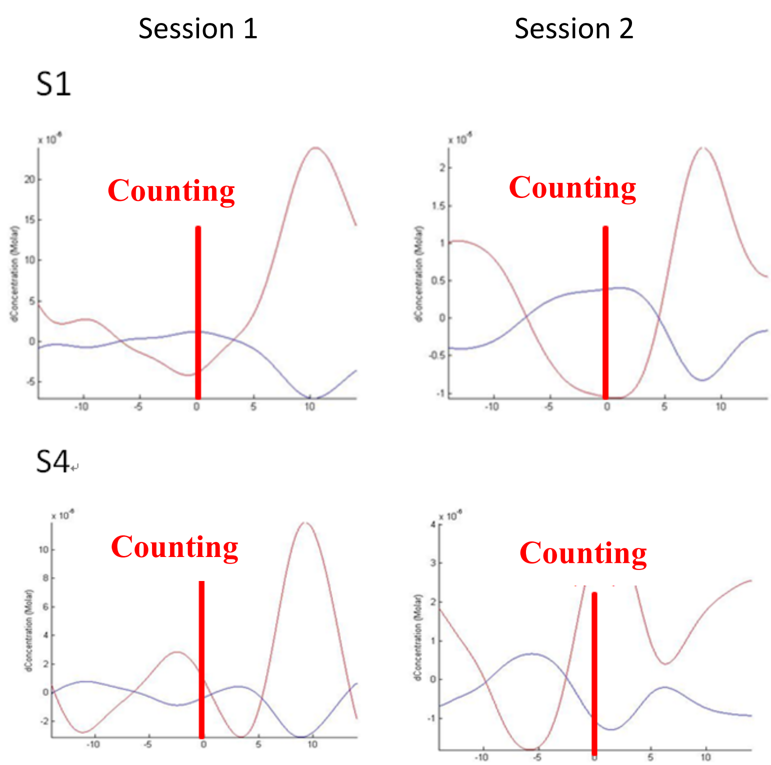
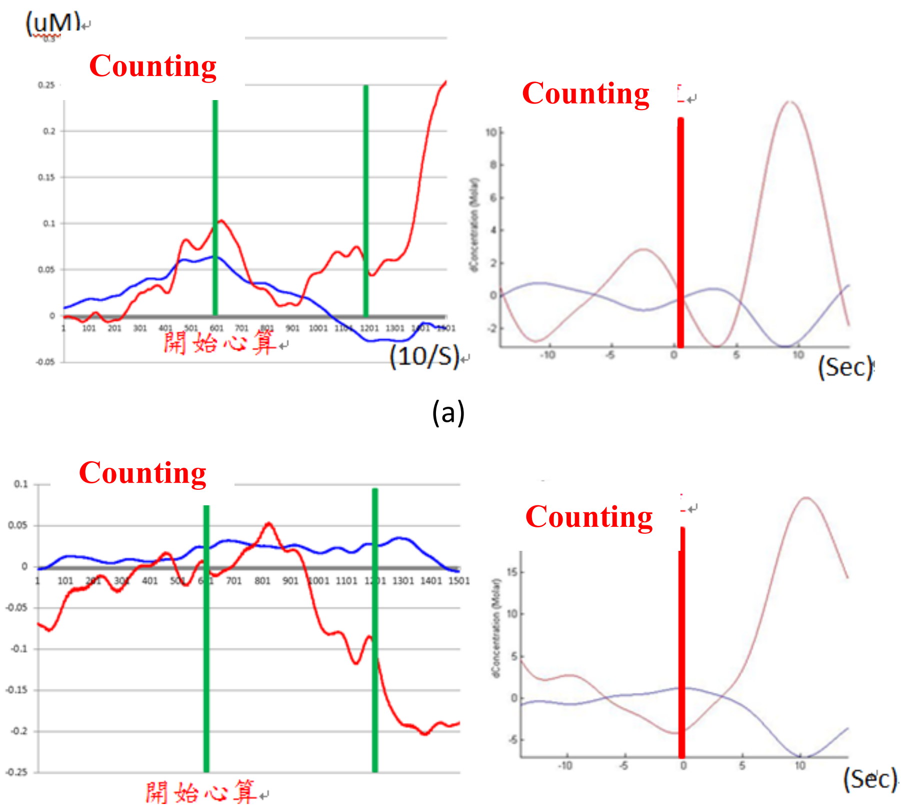


Figure 9. The result of the mental arithmetic experiments

To compare with a commercially available NIRS system, we also conducted the same cogntiitve experiment on the same subjects using the Hitachi ETG-4000 system. Figure 10 shows the comparison results between our NIRS system and ETG-4000 system.



(a)

(b)

Figure 10. The results of the mental arithmetic experiments. Left panels were recorded by ETG-4000, and right panels were recorded by the proposed NIRS system.

4. Development of signal-processing methods to improve the fidelity of EEG recordings and extract brain activities in the recordings

4.1 On-line recursive ICA

EEG data collected by dry electrodes and NIR sensors are subject to severe motion, ocular and muscle artifacts. Methods are needed to remove these sources of EEG contamination. Over the past decade, investigators of this proposal [Makeig et al., 1996; Jung et al., 1998; 2000a; 2000b] have developed a generally applicable method for isolating and removing a wide variety of EEG artifacts by linear decomposition using independent component analysis (ICA) [Bell and Sejnowski, 1995]. Despite such successes, more development and testing are needed to make the algorithms feasible for robustly and continuously correcting artifacts in the EEG data from unconstrained, freely-moving subjects in everyday environments. As the dry EEG sensors will not have direct connect to the scalp, the locations of sensors with respect to the scalp will change from time to time, ICA-based artifact-correction mechanism thus needs to be able to derive the varying unmixing matrix accordingly. In other words, we need to develop an on-line ICA algorithm or algorithms for EEG monitoring in real-world environments. During the past two years, we have developed a new recursive algorithm for incremental estimation of independent components from on-line data. The algorithm offers the convergence properties of batch ICA with incremental updates of a form similar to natural gradient (NG) on-line information maximization (Infomax). We found significant gains in convergence rate over on-line natural gradient ICA [Akhtar, et al., 2012; Hsu et al, under review].

4.2 Online automatic artifact correction

In the past few months, we further developed and implemented real-time artifact correction algorithms, Artifact Subspace Reconstruction (ASR), for online and real-time rejection of EEG artifacts that occur and are estimated on a short (1-min) time scale and are contained in a low-dimensional spatial data subspace [Mullen et al., 2013]. ASR is a highly effective and robust spatial artifact rejection that intuitively finds and projects high-amplitude artifact subspaces out of the data. The method can be feasibly applied in near-real time to data containing a variety of artifacts. The algorithm is built upon BCILAB [Kothe & Makeig, 2013], an EEGLAB plugin for the design, prototyping, testing, experimentation with, and evaluation of Brain-Computer Interfaces (BCIs), and other systems in the same computational framework. Figure 11 below shows a segment of EEG data contaminated by blink and muscle artifacts, before and after ASR artifact removal.

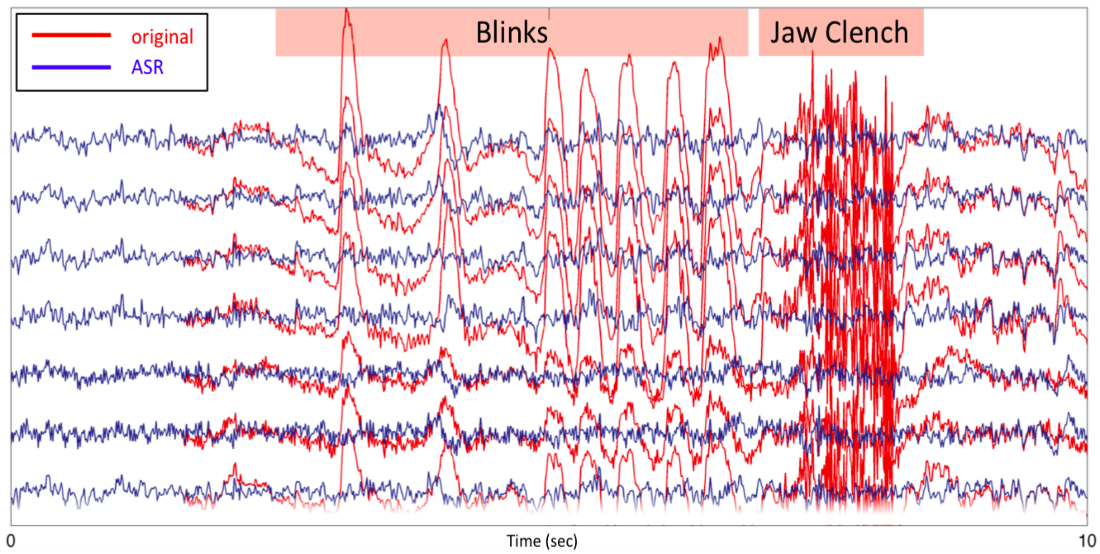


Figure 11. 10 sec of EEG data following ASR data cleaning (blue trace) superimposed on original data (red trace). Figure is copied from [Mullen et al., 2013].

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6. COLLABORATIONS AND LEVERAGED FUNDING

Leveraged Funding. Co-PIs of this study joined a Research Consortium which won a five-year contract from Army Research Laboratory (ARL) Cognition and Neuroergonomics (CAN) program in 2010. The project is to develop and demonstrate basic cognitive neuroscience principles guiding development of improved human-systems interactions in complex information environments. Under the CAN program, a Collaborative Technology Alliance (CTA) has been formed by the U.S. ARL and our Research Consortium to explore basic scientific knowledge in neuroscience, human factors, psychology, and engineering to enhance our understanding of Soldier brain function and behavior in complex operational settings, assessed outside the confines of standard research laboratories. This study of developing an innovative EEG/fNIR system and the new CAN-CTA project are complimentary as this study is developing new sensors to measure simultaneous EEG and fNIR signals of wearers, whereas the CAN-CTA provides an unparalleled platform for us to test and explore military applications of our new neuroimaging modality.

Collaborations. We recently visited Dr. Harold Szu of U.S. Army Night Vision & Electronic Sensors Directorate (NVESD) to discuss potential applications of new brain imaging modality.

7. CONCLUSIONS

This study designed, developed, and tested a portable, lightweight, noninvasive neuroimaging system that supported simultaneous EEG and functional NIR acquisition for biological or cognitive neuroscience studies. Over the past few years, we have developed novel EEG/NIRS electro-opodes that allow non-invasive acquisition of EEG and fNIR signals, and miniaturized supporting hardware/software. We then conducted three experiments to demonstrate the feasibility of non-invasive and non-intrusive acquisition of EEG and fNIR signals. We have also developed and implemented real-time artifact correction algorithms, Artifact Subspace Reconstruction, for online and real-time rejection of EEG artifacts in operational environments. Future work includes testing of the VLSI neuroimaging chip and a systematic evaluation of the entire EEG/fNIR system in several cognitive experiments.

TECHNOLOGY TRANSFER

As mentioned above, we have initiated collaboration between ARL-HRED, ARL-NVESD and UCSD. We plan to conduct laboratory and field tests of the new imaging modality under the current CAN-CTA.

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