fNIRS Publications by Application

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Alternative Medicine

Acupuncture, interactions of herbal medicines with conventional drugs, pain management, meditation, Yoga, Tai Chi, Qi Gong, and others are techniques whose serious inquiry is well supported by fNIRS. NIRx experts can help you plan experimental strategies best suited to explore such nontraditional but promising methods.

[1] G. Litscher, G. Bauernfeind, X. Gao, G. Mueller-Putz, L. Wang, W. Anderle, I. Gaischek, D. Litscher, C. Neuper, and R. C. Niemtzow, "Battlefield Acupuncture and Near-Infrared Spectroscopy–Miniaturized Computer-Triggered Electrical Stimulation of Battlefield Ear Acupuncture Points and 50-Channel Near-Infrared Spectroscopic Mapping," Medical Acupuncture, vol. 23, no. 4, pp. 263–270, Dec. 2011.

Please visit: https://nccih.nih.gov/, for latest updates on complementary and integrative health strategies.

Auditory

As fNIRS measurements are characterized by silent operations, innumerous possibilities of studies intended to explore the cortical activation in the presence of controlled sounds can be achieved. In addition to a better understanding of the underlying auditory processes in the brain, this may enable critical improvements on current solutions for cochlear implants.

[1] C. Olds, L. Pollonini, H. Abaya, J. Larky, M. Loy, H. Bortfeld, M. S. Beauchamp, and J. S. Oghalai, "Cortical Activation Patterns Correlate with Speech Understanding After Cochlear Implantation," Ear Hear, vol. 37, no. 3, pp. e160-172, Jun. 2016.

[2] K.-S. Hong and H. Santosa, "Decoding four different sound-categories in the auditory cortex using functional near-infrared spectroscopy," Hearing Research, vol. 333, pp. 157–166, Mar. 2016.

[3] L.-C. Chen, M. Stropahl, M. Schönwiesner, and S. Debener, "Enhanced visual adaptation in cochlear implant users revealed by concurrent EEG-fNIRS," *Neuroimage*, Sep. 2016.

[4] L.-C. Chen, P. Sandmann, J. D. Thorne, M. G. Bleichner, and S. Debener, "Cross-Modal Functional Reorganization of Visual and Auditory Cortex in Adult Cochlear Implant Users Identified with fNIRS," Neural Plast, vol. 2016, 2016.

[5] N. Altvater-Mackensen and T. Grossmann, "The role of left inferior frontal cortex during audiovisual speech perception in infants," NeuroImage, vol. 133, pp. 14–20, Jun. 2016.

[6] N. Abboub, T. Nazzi, and J. Gervain, "Prosodic grouping at birth," Brain Lang, vol. 162, pp. 46–59, Aug. 2016.

[7] L.-C. Chen, P. Sandmann, J. D. Thorne, C. S. Herrmann, and S. Debener, "Association of Concurrent fNIRS and EEG Signatures in Response to Auditory and Visual Stimuli," Brain Topogr, vol. 28, no. 5, pp. 710–725, Sep. 2015.

[8] C. Bouchon, T. Nazzi, and J. Gervain, "Hemispheric Asymmetries in Repetition Enhancement and Suppression Effects in the Newborn Brain," PLOS ONE, vol. 10, no. 10, p. e0140160, Oct. 2015.

[9] H. Santosa, M. J. Hong, and K.-S. Hong, "Lateralization of music processing with noises in the auditory cortex: an fNIRS study," Front Behav Neurosci, vol. 8, p. 418, 2014.

[10] L. Pollonini, C. Olds, H. Abaya, H. Bortfeld, M. S. Beauchamp, and J. S. Oghalai, "Auditory cortex activation to natural speech and simulated cochlear implant speech measured with functional near-infrared spectroscopy," Hear. Res., vol. 309, pp. 84–93, Mar. 2014.

[11] T. T. Brink, K. Urton, D. Held, E. Kirilina, M. J. Hofmann, G. Klann-Delius, A. M. Jacobs, and L. Kuchinke, "The role of orbitofrontal cortex in processing empathy stories in 4- to 8-year-old children," Front Psychol, vol. 2, p. 80, 2011.

Please visit: http://www.nidcd.nih.gov/Pages/default.aspx, for latest updates on health information pertaining to hearing, balance, taste, smell, and speech and language development.

Brain-Computer Interface (BCI)

Given its great performance in the presence of muscle movements and the possibility of setting up measurements on realistic environments, fNIRS presents itself as an optimal candidate to acquire cortical signals as reliable and representative inputs for a Brain-Computer Interface investigation.

[1] N. Naseer, F. M. Noori, N. K. Qureshi, and K.-S. Hong, "Determining Optimal Feature-Combination for LDA Classification of Functional Near-Infrared Spectroscopy Signals in Brain-Computer Interface Application," Front. Hum. Neurosci, p. 237, 2016.

[2] K.-S. Hong and H. Santosa, "Decoding four different sound-categories in the auditory cortex using functional near-infrared spectroscopy," Hearing Research, vol. 333, pp. 157–166, Mar. 2016.

[3] A. P. Buccino, H. O. Keles, and A. Omurtag, "Hybrid EEG-fNIRS Asynchronous Brain-Computer Interface for Multiple Motor Tasks," PLOS ONE, vol. 11, no. 1, p. e0146610, Jan. 2016.

[4] K. Tumanov, R. Goebel, R. Möckel, B. Sorger, and G. Weiss, "fNIRS-based BCI for Robot Control," in Proceedings of the 2015 International Conference on Autonomous Agents and Multiagent Systems, Richland, SC, 2015, pp. 1953–1954.

[5] N. Naseer and K.-S. Hong, "Decoding answers to four-choice questions using functional near infrared spectroscopy," J. Near Infrared Spectrosc, vol. 23, no. 1, pp. 23–31, 2015.

[6] M.-H. Lee, S. Fazli, J. Mehnert, and S.-W. Lee, "Subject-dependent classification for robust idle state detection using multi-modal neuroimaging and data-fusion techniques in BCI," Pattern Recognition, vol. 48, no. 8, pp. 2725–2737, Aug. 2015.

[7] M. J. Khan and K.-S. Hong, "Passive BCI based on drowsiness detection: an fNIRS study," Biomed Opt Express, vol. 6, no. 10, pp. 4063–4078, Oct. 2015.

[8] K.-S. Hong, N. Naseer, and Y.-H. Kim, "Classification of prefrontal and motor cortex signals for three-class fNIRS–BCI," Neuroscience Letters, vol. 587, pp. 87–92, Feb. 2015.
[9] R. K. Almajidy, Y. Boudria, U. G. Hofmann, W. Besio, and K. Mankodiya, "Multimodal 2D Brain Computer Interface," in 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015, pp. 1067–1070.

[10] M. J. Khan, M. J. Hong, and K.-S. Hong, "Decoding of four movement directions using hybrid NIRS-EEG brain-computer interface," Front Hum Neurosci, vol. 8, p. 244, 2014.

[11] C.-H. Chen, M.-S. Ho, K.-K. Shyu, K.-C. Hsu, K.-W. Wang, and P.-L. Lee, "A noninvasive brain computer interface using visually-induced near-infrared spectroscopy responses," Neuroscience Letters, vol. 580, pp. 22–26, Sep. 2014.

[12] N. Naseer, M. J. Hong, and K.-S. Hong, "Online binary decision decoding using functional near-infrared spectroscopy for the development of brain–computer interface," Exp Brain Res, vol. 232, no. 2, pp. 555–564, Nov. 2013.

[13] M. M. DiStasio and J. T. Francis, "Use of frontal lobe hemodynamics as reinforcement signals to an adaptive controller," PLoS ONE, vol. 8, no. 7, p. e69541, 2013.

[14] S. Waldert, L. Tüshaus, C. P. Kaller, A. Aertsen, and C. Mehring, "fNIRS Exhibits Weak Tuning to Hand Movement Direction," PLOS ONE, vol. 7, no. 11, p. e49266, Nov. 2012.

[15] X.-S. Hu, K.-S. Hong, and S. S. Ge, "fNIRS-based online deception decoding," J Neural Eng, vol. 9, no. 2, p. 26012, Apr. 2012.

[16] C. Herff, F. Putze, D. Heger, C. Guan, and T. Schultz, “Speaking mode recognition from functional Near Infrared Spectroscopy,” Conf Proc IEEE Eng Med Biol Soc, vol. 2012, pp. 1715–1718, 2012.

[17] S. Fazli, J. Mehnert, J. Steinbrink, G. Curio, A. Villringer, K.-R. Müller, and B. Blankertz, “Enhanced performance by a hybrid NIRS-EEG brain computer interface,” Neuroimage, vol. 59, no. 1, pp. 519–529, Jan. 2012.

[18] S. Fazli, J. Mehnert, J. Steinbrink, and B. Blankertz, “Using NIRS as a predictor for EEG-based BCI performance,”Conf Proc IEEE Eng Med Biol Soc, vol. 2012, pp. 4911–4914, 2012.

[19] V. Gottemukkula and R. Derakhshani, “Classification-guided feature selection for NIRS-based BCI,” in 2011 5th International IEEE/EMBS Conference on Neural Engineering (NER), 2011, pp. 72–75.

Please visit: http://www.nibib.nih.gov/news-events/newsroom/brain-computer-interfaces-come-home; http://www.nidcd.nih.gov/funding/programs/npp/Pages/workshop_bci_summary.aspx; http://www.sciencedirect.com/science/article/pii/S0165027014002702, for latest updates on NIH and DARPA funded efforts for BCI funded research.

Brain Perfusion

Brain perfusion assessment on clinical environment has been mostly performed by techniques that cannot accomplish constant monitoring of the brain. Because of its intrinsic capability of constant monitoring as well as the unique portability, fNIRS has clear potential to be applied for intensive care unit applications.

[1] M. Tessari, A. M. Malagoni, M. E. Vannini, and P. Zamboni, “A novel device for non-invasive cerebral perfusion assessment,” Veins and Lymphatics, vol. 4, no. 1, Mar. 2015.

[2] J. Stojanovic-Radic, G. Wylie, G. Voelbel, N. Chiaravalloti, and J. DeLuca, “Neuroimaging and cognition using functional near infrared spectroscopy (fNIRS) in multiple sclerosis,” Brain Imaging Behav, vol. 9, no. 2, pp. 302–311, Jun. 2015.

[3] C. Habermehl, C. H. Schmitz, and J. Steinbrink, “Contrast enhanced high-resolution diffuse optical tomography of the human brain using ICG,” Opt Express, vol. 19, no. 19, pp. 18636–18644, Sep. 2011.

Clinical Neurology

fNIRS capabilities of constant monitoring of oxygenation, perfusion and autoregulation results on a high potential for future application of the technique on diagnosis for cerebrovascular disease and severe brain injury. Other clinical neurology methodologies including epileptic disorders and central nervous system tumors may benefit from the technique on the preoperative function localization.

[1] S. E. Kober, G. Bauernfeind, C. Woller, M. Sampl, P. Grieshofer, C. Neuper, and G. Wood, “Hemodynamic Signal Changes Accompanying Execution and Imagery of Swallowing in Patients with Dysphagia: A Multiple Single-Case Near-Infrared Spectroscopy Study,” Front Neurol, vol. 6, Jul. 2015.

[2] H. Obrig, “NIRS in clinical neurology - a ‘promising’ tool?,” Neuroimage, vol. 85 Pt 1, pp. 535–546, Jan. 2014.

Cognitive States

Cognitive functions and mental states can be widely explored with fNIRS since this is a portable technique that is not too sensitive to motion artifacts. Attention, working memory, decision making, among other applications may be studied in natural environments with a fast setup preparation.

[1] J. Stojanovic-Radic, G. Wylie, G. Voelbel, N. Chiaravalloti, and J. DeLuca, "Neuroimaging and cognition using functional near infrared spectroscopy (fNIRS) in multiple sclerosis," Brain Imaging Behav, vol. 9, no. 2, pp. 302–311, Jun. 2015.

[2] N. Naseer and K.-S. Hong, "Decoding answers to four-choice questions using functional near infrared spectroscopy," J. Near Infrared Spectrosc, vol. 23, no. 1, pp. 23–31, 2015.

[3] M. J. Khan and K.-S. Hong, "Passive BCI based on drowsiness detection: an fNIRS study," Biomed Opt Express, vol. 6, no. 10, pp. 4063–4078, Oct. 2015.

[4] K.-S. Hong, N. Naseer, and Y.-H. Kim, "Classification of prefrontal and motor cortex signals for three-class fNIRS–BCI," Neuroscience Letters, vol. 587, pp. 87–92, Feb. 2015.

[5] M. J. Khan, M. J. Hong, and K.-S. Hong, "Decoding of four movement directions using hybrid NIRS-EEG brain-computer interface," Front Hum Neurosci, vol. 8, p. 244, 2014.

[6] M. A. Kamran and K.-S. Hong, "Reduction of physiological effects in fNIRS waveforms for efficient brain-state decoding," Neurosci. Lett., vol. 580, pp. 130–136, Sep. 2014.
[7] C. Bogler, J. Mehnert, J. Steinbrink, and J.-D. Haynes, "Decoding vigilance with NIRS," PLoS ONE, vol. 9, no. 7, p. e101729, 2014.

[8] J. Bahnmueller, T. Dresler, A.-C. Ehlis, U. Cress, and H.-C. Nuerk, "NIRS in motion—unraveling the neurocognitive underpinnings of embodied numerical cognition," Front. Psychol, vol. 5, p. 743, 2014.

[9] N. Naseer, M. J. Hong, and K.-S. Hong, "Online binary decision decoding using functional near-infrared spectroscopy for the development of brain–computer interface," Exp Brain Res, vol. 232, no. 2, pp. 555–564, Nov. 2013.

[10] M. M. DiStasio and J. T. Francis, "Use of frontal lobe hemodynamics as reinforcement signals to an adaptive controller," PLoS ONE, vol. 8, no. 7, p. e69541, 2013.

[11] X.-S. Hu, K.-S. Hong, and S. S. Ge, "fNIRS-based online deception decoding," J Neural Eng, vol. 9, no. 2, p. 26012, Apr. 2012.

Please visit:
http://www.nimh.nih.gov/labs-at-nimh/research-areas/clinics-and-labs/lbc/index.shtml, for latest description on NIH's intramural efforts to explore cognition and its influences on mental health.

Connectivity

fNIRS can bring connectivity studies to a new level of applications with the hyperscanning modality, which enables both online feedback as well as offline analysis regarding within- and between-subjects connectivity. In addition to that, fNIRS fast sampling rate for hemodynamic states allows for a quick update rate of connectivity feedback, representing a higher subject engagement to the task.

[1] S. Tak, A. M. Kempny, K. J. Friston, A. P. Leff, and W. D. Penny, "Dynamic causal modelling for functional near-infrared spectroscopy," Neuroimage, vol. 111, pp. 338–349, May 2015.

[2] L. Holper, F. Scholkmann, and E. Seifritz, "Time-frequency dynamics of the sum of intra- and extracerebral hemodynamic functional connectivity during resting-state and respiratory challenges assessed by multimodal functional near-infrared spectroscopy," Neuroimage, vol. 120, pp. 481–492, Oct. 2015.

[3] J. Mehnert, A. Akhrif, S. Telkemeyer, S. Rossi, C. H. Schmitz, J. Steinbrink, I. Wartenburger, H. Obrig, and S. Neufang, "Developmental changes in brain activation and functional connectivity during response inhibition in the early childhood brain," Brain Dev., vol. 35, no. 10, pp. 894–904, Nov. 2013.

[4] R. L. Barbour, H. L. Graber, Y. Xu, Y. Pei, C. H. Schmitz, D. S. Pfeil, A. Tyagi, R. Andronica, D. C. Lee, S.-L. S. Barbour, J. D. Nichols, and M. E. Pflieger, “A programmable laboratory testbed in support of evaluation of functional brain activation and connectivity,” IEEE Trans Neural Syst Rehabil Eng, vol. 20, no. 2, pp. 170–183, Mar. 2012.

[5] H. Niu, S. Khadka, F. Tian, Z.-J. Lin, C. Lu, C. Zhu, and H. Liu, “Resting-state functional connectivity assessed with two diffuse optical tomographic systems,” J Biomed Opt, vol. 16, no. 4, p. 46006, Apr. 2011.

[6] J. Mehnert, C. Schmitz, H. E. Möller, H. Obrig, and K. Mueller, Simultaneous optical tomography (OT) and fMRI with and without task activation. 2010.

Developmental Changes

The portability of the technique, performance in presence of general movements and feasibility to explore cortical response to social interactions represent the greatest advantages of fNIRS towards studies on brain functional changes during development of infants and children.

[1] C. Bouchon, T. Nazzi, and J. Gervain, “Hemispheric Asymmetries in Repetition Enhancement and Suppression Effects in the Newborn Brain,” PLOS ONE, vol. 10, no. 10, p. e0140160, Oct. 2015.

[2] J. Mehnert, A. Akhrif, S. Telkemeyer, S. Rossi, C. H. Schmitz, J. Steinbrink, I. Wartenburger, H. Obrig, and S. Neufang, “Developmental changes in brain activation and functional connectivity during response inhibition in the early childhood brain,” Brain Dev., vol. 35, no. 10, pp. 894–904, Nov. 2013.

[3] T. T. Brink, K. Urton, D. Held, E. Kirilina, M. J. Hofmann, G. Klann-Delius, A. M. Jacobs, and L. Kuchinke, “The role of orbitofrontal cortex in processing empathy stories in 4- to 8-year-old children,” Front Psychol, vol. 2, p. 80, 2011.

Please visit: https://www.nichd.nih.gov/about/overview/directors_corner/Pages/default.aspx,
for updates from Dr. Catherine Spong, acting director of NICHD, on new program initiatives including: Learning Disabilities Innovation Hubs, Precision Medicine Initiative, Intellectual and Developmental Disabilities Research Centers among others.

Emotions

Our interaction with our environment and others often determines our emotional wellbeing. Its capacity to operate in the natural environment including measures involving interactive social settings makes fNIRS a powerful new tool in our efforts to understand the many features affecting emotional states.

[1] M. E. Vanutelli and M. Balconi, “Perceiving emotions in human-human and human-animal interactions: Hemodynamic prefrontal activity (fNIRS) and empathic concern,” Neurosci. Lett., vol. 605, pp. 1–6, Sep. 2015.

[2] M. Balconi and M. E. Vanutelli, “Emotions and BIS/BAS components affect brain activity (ERPs and fNIRS) in observing intra-species and inter-species interactions,” Brain Imaging and Behavior, vol. 10, no. 3, pp. 750–760, Aug. 2015.

[3] M. Balconi, E. Grippa, and M. E. Vanutelli, “What hemodynamic (fNIRS), electrophysiological (EEG) and autonomic integrated measures can tell us about emotional processing,” Brain Cogn, vol. 95, pp. 67–76, Apr. 2015.

[4] M. Balconi, E. Grippa, and M. E. Vanutelli, “Resting lateralized activity predicts the cortical response and appraisal of emotions: an fNIRS study,” Soc Cogn Affect Neurosci, vol. 10, no. 12, pp. 1607–1614, Dec. 2015.

Please visit: http://www.nimh.nih.gov/labs-at-nimh/research-areas/clinics-and-labs/edb/index.shtml, for description of the latest research updates from NIMH.

Event-Related Optical Signal

fNIRS is potentially the only imaging method that may be capable to measure both hemodynamics and neuronal activity. The Event-Related Optical Signal, caused by changes in light scattering from activated neurons, is observable when employing high frequency sampling with fNIRS.

[1] Hu, Xiao-Su, K.-S. Hong, and S.S. Ge, “Recognition of stimulus-evoked neuronal optical response by identifying chaos levels of near-infrared spectroscopy time series,” Neuroscience Letters 504, 115-120 (2011).

[2] Medvedev, A., J. Kainerstorfer, S.V. Borisov, R.L. Barbour, and J. VanMeter, “Event-related fast optical signal in a rapid object recognition task: Improving detection by the independent component analysis,” Brain Research 1236, 145-158 (2008).

Please visit:
http://www.nibib.nih.gov/science-education/science-topics/optical-imaging;
http://www.report.nih.gov/nihfactsheets/ViewFactSheet.aspx?csid=105, for an informative discussion on the various strategies of optical imaging techniques.

Infant Monitoring

Infant monitoring is based on continuous measurements of cortical activity within a population that may be characterized by its constant movement. fNIRS low sensitivity of motion artifacts and improved light penetration make this tool an ideal choice for studies intended to explore the many unknown features of infant brain development.

[1] N. Altvater-Mackensen and T. Grossmann, “The role of left inferior frontal cortex during audiovisual speech perception in infants,” NeuroImage, vol. 133, pp. 14–20, Jun. 2016.

[2] J. Gervain, “Plasticity in early language acquisition: the effects of prenatal and early childhood experience,” Curr. Opin. Neurobiol., vol. 35, pp. 13–20, Dec. 2015.

[3] C. Bouchon, T. Nazzi, and J. Gervain, “Hemispheric Asymmetries in Repetition Enhancement and Suppression Effects in the Newborn Brain,” PLOS ONE, vol. 10, no. 10, p. e0140160, Oct. 2015.

[4] S. R. Jadcherla, J. F. Pakiraih, K. A. Hasenstab, I. Dar, X. Gao, D. G. Bates, and N. H. Kashou, “Esophageal reflexes modulate frontoparietal response in neonates: Novel application of concurrent NIRS and provocative esophageal manometry,” American Journal of Physiology - Gastrointestinal and Liver Physiology, vol. 307, no. 1, pp. G41–G49, Jul. 2014.

Please visit: https://www.nlm.nih.gov/medlineplus/infantandnewborndevelopment.html, for an informative summary of time lines for sensory, motor and psychosocial development in infants and young children.

Multilingual Brain

There is growing evidence that children who learn more than one language have improved long-term outcomes. NIRx systems and technologies are currently supporting a European-wide study aimed at quantifying metrics of brain function in the bilingual child.

[1] Gervain, Judit. "Plasticity in early language acquisition: the effects of prenatal and early childhood experience." *Current opinion in neurobiology* 35 (2015): 13-20.

Please visit: http://cordis.europa.eu/project/rcn/193857_en.html, for outline of this exciting use of fNIRS technology from NIRx.

Also see, http://www.nichd.nih.gov/news/releases/Pages/022315-podcast-bilingualism.aspx

Motor Execution

Motor execution and fine movements depend on coordinated action of brain function with peripheral muscles. Portability, use in natural environments, and compatibility with bioelectric measures make fNIRS an optimal choice for any application related to motor execution.

[1] N. H. Kashou, B. M. Giacherio, R. W. Nahhas, and S. R. Jadcherla, "Hand-grasping and finger tapping induced similar functional near-infrared spectroscopy cortical responses," *Neurophotonics*, vol. 3, no. 2, p. 25006, Apr. 2016.

[2] M.-H. Lee, B.-J. Kim, and S.-W. Lee, "Quantifying movement intentions with multimodal neuroimaging for functional electrical stimulation-based rehabilitation," Neuroreport, vol. 27, no. 2, pp. 61–66, Jan. 2016.

[3] D. Carius, C. Andrä, M. Clauß, P. Ragert, M. Bunk, and J. Mehnert, "Hemodynamic Response Alteration As a Function of Task Complexity and Expertise—An fNIRS Study in Jugglers," Front. Hum. Neurosci, p. 126, 2016.

[4] A. P. Buccino, H. O. Keles, and A. Omurtag, "Hybrid EEG-fNIRS Asynchronous Brain-Computer Interface for Multiple Motor Tasks," PLOS ONE, vol. 11, no. 1, p. e0146610, Jan. 2016.

[5] M. Balconi and L. Cortesi, "Brain Activity (fNIRS) in Control State Differs from the Execution and Observation of Object-Related and Object-Unrelated Actions," J Mot Behav, vol. 48, no. 4, pp. 289–296, Aug. 2016.

[6] S. Tak, A. M. Kempny, K. J. Friston, A. P. Leff, and W. D. Penny, "Dynamic causal modelling for functional near-infrared spectroscopy," Neuroimage, vol. 111, pp. 338–349, May 2015.

[7] C.-F. Lu, Y.-C. Liu, Y.-R. Yang, Y.-T. Wu, and R.-Y. Wang, "Maintaining Gait Performance by Cortical Activation during Dual-Task Interference: A Functional Near-Infrared Spectroscopy Study," PLOS ONE, vol. 10, no. 6, p. e0129390, Jun. 2015.

[8] S. E. Kober, G. Bauernfeind, C. Woller, M. Sampl, P. Grieshofer, C. Neuper, and G. Wood, "Hemodynamic Signal Changes Accompanying Execution and Imagery of Swallowing in Patients with Dysphagia: A Multiple Single-Case Near-Infrared Spectroscopy Study," Front Neurol, vol. 6, Jul. 2015.

[9] I. Helmich, H. Holle, R. Rein, and H. Lausberg, "Brain oxygenation patterns during the execution of tool use demonstration, tool use pantomime, and body-part-as-object tool use," Int J Psychophysiol, vol. 96, no. 1, pp. 1–7, Apr. 2015.

[10] M. Brunetti, N. Morkisch, C. Fritzsch, J. Mehnert, J. Steinbrink, M. Niedeggen, and C. Dohle, "Potential determinants of efficacy of mirror therapy in stroke patients--A pilot study," Restor. Neurol. Neurosci., vol. 33, no. 4, pp. 421–434, 2015.

[11] S. K. Piper, A. Krueger, S. P. Koch, J. Mehnert, C. Habermehl, J. Steinbrink, H. Obrig, and C. H. Schmitz, "A wearable multi-channel fNIRS system for brain imaging in freely moving subjects," Neuroimage, vol. 85 Pt 1, pp. 64–71, Jan. 2014.

[12] M. J. Khan, M. J. Hong, and K.-S. Hong, "Decoding of four movement directions using hybrid NIRS-EEG brain-computer interface," Front Hum Neurosci, vol. 8, p. 244, 2014.

[13] K.-S. Hong and H.-D. Nguyen, "State-space models of impulse hemodynamic responses over motor, somatosensory, and visual cortices," Biomed Opt Express, vol. 5, no. 6, pp. 1778–1798, May 2014.

[14] R. Beurskens, I. Helmich, R. Rein, and O. Bock, "Age-related changes in prefrontal activity during walking in dual-task situations: A fNIRS study," International Journal of Psychophysiology, vol. 92, no. 3, pp. 122–128, Jun. 2014.

[15] I. Helmich, R. Rein, N. Niermann, and H. Lausberg, “Hemispheric differences of motor execution: a near-infrared spectroscopy study,” Adv. Exp. Med. Biol., vol. 789, pp. 59–64, 2013.

[16] S. Waldert, L. Tüshaus, C. P. Kaller, A. Aertsen, and C. Mehring, “fNIRS Exhibits Weak Tuning to Hand Movement Direction,” PLOS ONE, vol. 7, no. 11, p. e49266, Nov. 2012.

Multi-modal

In order to render measurements more robust and with a great amount of information provided by different methods, many groups appreciate multi-modal applications with fNIRS. Typical modalities are EEG, Eye-Tracking and fMRI, while tDCS and TMS may also be applied to modulate brain activity.

[1] H. Obrig, J. Mock, F. Stephan, M. Richter, M. Vignotto, and S. Rossi, “Impact of associative word learning on phonotactic processing in 6-month-old infants: A combined EEG and fNIRS study,” Developmental Cognitive Neuroscience.

[2] L.-C. Chen, M. Stropahl, M. Schönwiesner, and S. Debener, “Enhanced visual adaptation in cochlear implant users revealed by concurrent EEG-fNIRS,” Neuroimage, Sep. 2016.

[3] L. Zhu, A. E. Haddad, T. Zeng, Y. Wang, and L. Najafizadeh, “Assessing Optimal Electrode/Optode Arrangement in EEG-fNIRS Multi-Modal Imaging,” in Biomedical Optics 2016, 2016, p. paper–JW3A.

[4] M.-H. Lee, B.-J. Kim, and S.-W. Lee, “Quantifying movement intentions with multimodal neuroimaging for functional electrical stimulation-based rehabilitation,” Neuroreport, vol. 27, no. 2, pp. 61–66, Jan. 2016.

[5] H. O. Keles, R. L. Barbour, and A. Omurtag, “Hemodynamic correlates of spontaneous neural activity measured by human whole-head resting state EEG+fNIRS,” Neuroimage, vol. 138, pp. 76–87, Sep. 2016.

[6] L. Holper, F. Scholkmann, and E. Seifritz, “Prefrontal hemodynamic after-effects caused by rebreathing may predict affective states - A multimodal functional near-infrared spectroscopy study,” Brain Imaging Behav, Mar. 2016.

[7] T. Geall, “Could new ‘Matrix’ hat mean we can learn new skills in no time at all?,” mirror, 29-Feb-2016. [Online]. Available: http://www.mirror.co.uk/news/technology-science/science/scientists-develop-matrix-style-technique-7463286. [Accessed: 06-Oct-2016].

[8] D. Carius, C. Andrä, M. Clauß, P. Ragert, M. Bunk, and J. Mehnert, “Hemodynamic Response Alteration As a Function of Task Complexity and Expertise—An fNIRS Study in Jugglers,” Front. Hum. Neurosci, p. 126, 2016.

[9] A. P. Buccino, H. O. Keles, and A. Omurtag, “Hybrid EEG-fNIRS Asynchronous Brain-Computer Interface for Multiple Motor Tasks,” PLOS ONE, vol. 11, no. 1, p. e0146610, Jan. 2016.

[10] N. Altvater-Mackensen and T. Grossmann, “The role of left inferior frontal cortex during audiovisual speech perception in infants,” NeuroImage, vol. 133, pp. 14–20, Jun. 2016.

[11] A. D. Zaidi et al., “Simultaneous epidural functional near-infrared spectroscopy and cortical electrophysiology as a tool for studying local neurovascular coupling in primates,” Neuroimage, vol. 120, pp. 394–399, Oct. 2015.

[12] E. Maggioni et al., “Investigation of negative BOLD responses in human brain through NIRS technique. A visual stimulation study,” NeuroImage, vol. 108, pp. 410–422, Mar. 2015.

[13] M.-H. Lee, S. Fazli, J. Mehnert, and S.-W. Lee, “Subject-dependent classification for robust idle state detection using multi-modal neuroimaging and data-fusion techniques in BCI,” Pattern Recognition, vol. 48, no. 8, pp. 2725–2737, Aug. 2015.

[14] L.-C. Chen, P. Sandmann, J. D. Thorne, C. S. Herrmann, and S. Debener, “Association of Concurrent fNIRS and EEG Signatures in Response to Auditory and Visual Stimuli,” Brain Topogr, vol. 28, no. 5, pp. 710–725, Sep. 2015.

[15] M. Brunetti et al., "Potential determinants of efficacy of mirror therapy in stroke patients--A pilot study," Restor. Neurol. Neurosci., vol. 33, no. 4, pp. 421–434, 2015.

[16] M. Balconi and M. E. Vanutelli, "Emotions and BIS/BAS components affect brain activity (ERPs and fNIRS) in observing intra-species and inter-species interactions," Brain Imaging and Behavior, vol. 10, no. 3, pp. 750–760, Aug. 2015.

[17] M. Balconi, E. Grippa, and M. E. Vanutelli, "What hemodynamic (fNIRS), electrophysiological (EEG) and autonomic integrated measures can tell us about emotional processing," Brain Cogn, vol. 95, pp. 67–76, Apr. 2015.

[18] R. K. Almajidy, Y. Boudria, U. G. Hofmann, W. Besio, and K. Mankodiya, "Multimodal 2D Brain Computer Interface," in 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015, pp. 1067–1070.

[19] V. V. Nikulin et al., "Monochromatic ultra-slow (~0.1 Hz) oscillations in the human electroencephalogram and their relation to hemodynamics," Neuroimage, vol. 97, pp. 71–80, Aug. 2014.

[20] I. M. Kopton and P. Kenning, "Near-infrared spectroscopy (NIRS) as a new tool for neuroeconomic research," Front Hum Neurosci, vol. 8, Aug. 2014.

[21] M. J. Khan, M. J. Hong, and K.-S. Hong, "Decoding of four movement directions using hybrid NIRS-EEG brain-computer interface," Front Hum Neurosci, vol. 8, p. 244, 2014.

[22] E. Maggioni et al., "Coupling of fMRI and NIRS measurements in the study of negative BOLD response to intermittent photic stimulation," in 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2013, pp. 1378–1381.

[23] S. Dähne, F. Bießmann, F. C. Meinecke, J. Mehnert, S. Fazli, and K. R. Müller, "Integration of Multivariate Data Streams With Bandpower Signals," IEEE Transactions on Multimedia, vol. 15, no. 5, pp. 1001–1013, Aug. 2013.

[24] S. Fazli et al., "Enhanced performance by a hybrid NIRS-EEG brain computer interface," Neuroimage, vol. 59, no. 1, pp. 519–529, Jan. 2012.

[25] S. Fazli, J. Mehnert, J. Steinbrink, and B. Blankertz, "Using NIRS as a predictor for EEG-based BCI performance," Conf Proc IEEE Eng Med Biol Soc, vol. 2012, pp. 4911–4914, 2012.

[26] R. L. Barbour et al., "A programmable laboratory testbed in support of evaluation of functional brain activation and connectivity," IEEE Trans Neural Syst Rehabil Eng, vol. 20, no. 2, pp. 170–183, Mar. 2012.

Naturalistic Environment

With the advent of portable and wearable solutions, in addition to the intrinsic performance in the presence of movements, functional Near-Infrared Spectroscopy is currently the ideal solution for any studies that intend to evaluate the cortical activation within environments most similar to the reality.

[1] D. Carius, C. Andrä, M. Clauß, P. Ragert, M. Bunk, and J. Mehnert, "Hemodynamic Response Alteration As a Function of Task Complexity and Expertise—An fNIRS Study in Jugglers," Front. Hum. Neurosci, p. 126, 2016.

[2] C.-F. Lu, Y.-C. Liu, Y.-R. Yang, Y.-T. Wu, and R.-Y. Wang, "Maintaining Gait Performance by Cortical Activation during Dual-Task Interference: A Functional Near-Infrared Spectroscopy Study," PLOS ONE, vol. 10, no. 6, p. e0129390, Jun. 2015.

[3] I. Helmich, H. Holle, R. Rein, and H. Lausberg, "Brain oxygenation patterns during the execution of tool use demonstration, tool use pantomime, and body-part-as-object tool use," Int J Psychophysiol, vol. 96, no. 1, pp. 1–7, Apr. 2015.

[4] M. Brunetti, N. Morkisch, C. Fritzsch, J. Mehnert, J. Steinbrink, M. Niedeggen, and C. Dohle, "Potential determinants of efficacy of mirror therapy in stroke patients--A pilot study," Restor. Neurol. Neurosci., vol. 33, no. 4, pp. 421–434, 2015.

[5] S. K. Piper, A. Krueger, S. P. Koch, J. Mehnert, C. Habermehl, J. Steinbrink, H. Obrig, and C. H. Schmitz, "A wearable multi-channel fNIRS system for brain imaging in freely moving subjects," Neuroimage, vol. 85 Pt 1, pp. 64–71, Jan. 2014.

[6] J. Bahnmueller, T. Dresler, A.-C. Ehlis, U. Cress, and H.-C. Nuerk, "NIRS in motion—unraveling the neurocognitive underpinnings of embodied numerical cognition," Front. Psychol, vol. 5, p. 743, 2014.

Neuroeconomics

One of the pillars of neuroeconomics research is based on decision making, which may be evaluated from prefrontal lobe activity given a task. Although this has been explored with fMRI in the past, the restricted environment does impose a limit to the number of applications that can be explored. fNIRS may represent a notorious improvement to the field while enabling outdoor measurements that can be combined with simultaneous Eye-Tracking measurements.

[1] I. M. Kopton and P. Kenning, "Near-infrared spectroscopy (NIRS) as a new tool for neuroeconomic research," Front Hum Neurosci, vol. 8, Aug. 2014.

Pain Research

Having precise pain indicators obtained from brain activity can be particularly interesting to evaluate the efficiency of pain treatments, as well as to retrieve pain levels from people that may not be able to verbally communicate it. fNIRS, in particular, is a promising tool for this area giving its portability.

[1] K.-S. Hong and H.-D. Nguyen, "State-space models of impulse hemodynamic responses over motor, somatosensory, and visual cortices," Biomed Opt Express, vol. 5, no. 6, pp. 1778–1798, May 2014.

[2] J.-W. He, F. Tian, H. Liu, and Y. B. Peng, "Cerebrovascular responses of the rat brain to noxious stimuli as examined by functional near-infrared whole brain imaging," J. Neurophysiol., vol. 107, no. 10, pp. 2853–2865, May 2012.

Social Interaction

fNIRS ability of measuring two or more subjects at the same time enables researchers to study the effects of social interaction in the cortical activity. Possible applications on this area can be empathy, competitive and cooperative tasks, mother-child interactions, truth telling, among others. Also, this field may be explored by measuring activity from an individual interacting with animals, for example.

[1] M. Balconi and M. E. Vanutelli, "Competition in the Brain. The Contribution of EEG and fNIRS Modulation and Personality Effects in Social Ranking," Front. Psychol., p. 1587, 2016.

[2] M. E. Vanutelli and M. Balconi, "Perceiving emotions in human-human and human-animal interactions: Hemodynamic prefrontal activity (fNIRS) and empathic concern," Neurosci. Lett., vol. 605, pp. 1–6, Sep. 2015.

[3] M. Balconi and M. E. Vanutelli, "Emotions and BIS/BAS components affect brain activity (ERPs and fNIRS) in observing intra-species and inter-species interactions," Brain Imaging and Behavior, vol. 10, no. 3, pp. 750–760, Aug. 2015.

Somatosensory

[1] N. H. Kashou, I. A. Dar, K. A. Hasenstab, R. W. Nahhas, and S. R. Jadcherla, "Somatic stimulation causes frontoparietal cortical changes in neonates: a functional near-infrared spectroscopy study," Neurophotonics, vol. 4, no. 1, p. 11004, Jan. 2017.

[2] A. Vrana, M. L. Meier, S. Hotz-Boendermaker, B. K. Humphreys, and F. Scholkmann, "Different mechanosensory stimulations of the lower back elicit specific changes in hemodynamics and oxygenation in cortical sensorimotor areas—A fNIRS study," Brain Behav, p. n/a-n/a, Sep. 2016.

[3] K.-S. Hong and H.-D. Nguyen, "State-space models of impulse hemodynamic responses over motor, somatosensory, and visual cortices," Biomed Opt Express, vol. 5, no. 6, pp. 1778–1798, May 2014.

[4] C. Habermehl et al., "Somatosensory activation of two fingers can be discriminated with ultrahigh-density diffuse optical tomography," Neuroimage, vol. 59, no. 4, pp. 3201–3211, Feb. 2012.

Speech and Language

Realistic experiments involving verbalized speech should naturally account for the muscles required for this process and the eventual artifacts that these may cause. fNIRS robustness in the presence of muscle movements as well as its portability in comparison to other imaging techniques, render this technology a very promising tool for studying speech and language on a great variety of conditions.

[1] H. Obrig, J. Mock, F. Stephan, M. Richter, M. Vignotto, and S. Rossi, "Impact of associative word learning on phonotactic processing in 6-month-old infants: A combined EEG and fNIRS study," Developmental Cognitive Neuroscience.

[2] N. Altvater-Mackensen and T. Grossmann, "The role of left inferior frontal cortex during audiovisual speech perception in infants," NeuroImage, vol. 133, pp. 14–20, Jun. 2016.

[3] N. Abboub, T. Nazzi, and J. Gervain, "Prosodic grouping at birth," Brain Lang, vol. 162, pp. 46–59, Aug. 2016.

[4] C. Vitale, T. Murgallis, G. Tellis, and D. Anson, "Near-Infrared Spectroscopy Technology in Typically Fluent Speakers and Persons who Stutter," Procedia - Social and Behavioral Sciences, vol. 193, p. 354, Jun. 2015.

[5] J. Gervain, "Plasticity in early language acquisition: the effects of prenatal and early childhood experience," Curr. Opin. Neurobiol., vol. 35, pp. 13–20, Dec. 2015.

[6] C. Herff, F. Putze, D. Heger, C. Guan, and T. Schultz, "Speaking mode recognition from functional Near Infrared Spectroscopy," Conf Proc IEEE Eng Med Biol Soc, vol. 2012, pp. 1715–1718, 2012.

Stroke Rehabilitation

In addition to the advantages towards brain perfusion monitoring, stroke rehabilitation may benefit from fNIRS because of its portability and ease of application. These features allow for assessment during whole-body movements as well as neurofeedback methods indicators of the brain function, which may be of particular interest for training at home.

[1] C.-C. Lo and J.-J. J. Chen, "Design of Neurorehabilitation Device and Program for Stroke Patients Under Electrical Stimulation Assisted Cycling Using Near Infrared Spectroscopy1," J. Med. Devices, vol. 9, no. 3, pp. 030916–030916, Sep. 2015.

[2] S. E. Kober, G. Bauernfeind, C. Woller, M. Sampl, P. Grieshofer, C. Neuper, and G. Wood, "Hemodynamic Signal Changes Accompanying Execution and Imagery of Swallowing in Patients with Dysphagia: A Multiple Single-Case Near-Infrared Spectroscopy Study," Front Neurol, vol. 6, Jul. 2015.

[3] Z.-J. Lin, M. Ren, L. Li, Y. Liu, J. Su, S.-H. Yang, and H. Liu, "Interleaved imaging of cerebral hemodynamics and blood flow index to monitor ischemic stroke and treatment in rat by volumetric diffuse optical tomography,"Neuroimage, vol. 85 Pt 1, pp. 566–582, Jan. 2014.

[4] J. Mehnert, M. Brunetti, J. Steinbrink, M. Niedeggen, and C. Dohle, "Effect of a mirror-like illusion on activation in the precuneus assessed with functional near-infrared spectroscopy," J Biomed Opt, vol. 18, no. 6, p. 66001, Jun. 2013.

[5] H. Obrig and J. Steinbrink, "Non-invasive optical imaging of stroke," Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, vol. 369, no. 1955, pp. 4470–4494, Nov. 2011.

[6] C. Habermehl, C. H. Schmitz, and J. Steinbrink, "Contrast enhanced high-resolution diffuse optical tomography of the human brain using ICG," Opt Express, vol. 19, no. 19, pp. 18636–18644, Sep. 2011.

Technology Advances

The most often limitation of any research study is related to the limits offered by the technologies available. The efforts towards the design of new hardware and software solutions to overcome current limits are therefore much appreciated as they constantly push the technology state of the art and create a wide range of new possibilities to be explored by the whole research community.

[1] H.-D. Nguyen and K.-S. Hong, "Bundled-optode implementation for 3D imaging in functional near-infrared spectroscopy," Biomed Opt Express, vol. 7, no. 9, pp. 3491–3507, Aug. 2016.

[2] L. Holper, E. Seifritz, and F. Scholkmann, "Short-term pulse rate variability is better characterized by functional near-infrared spectroscopy than by photoplethysmography," J Biomed Opt, vol. 21, no. 9, p. 91308, Sep. 2016.

[3] J. Yao, F. Tian, Y. Rakvongthai, S. Oraintara, and H. Liu, "Quantification and normalization of noise variance with sparsity regularization to enhance diffuse optical tomography," Biomed Opt Express, vol. 6, no. 8, pp. 2961–2979, Aug. 2015.

[4] D. Piao, R. L. Barbour, H. L. Graber, and D. C. Lee, "On the geometry dependence of differential pathlength factor for near-infrared spectroscopy. I. Steady-state with homogeneous medium," J. Biomed. Opt, vol. 20, no. 10, pp. 105005–105005, 2015.

[5] H. D. Nguyen and K. S. Hong, "Multiple optodes configuration for measuring the absolute hemodynamic response using spatially resolved spectroscopy method: An fNIRS study," in 2015 15th International Conference on Control, Automation and Systems (ICCAS), 2015, pp. 1827–1832.

[6] M. A. Kamran, M. Y. Jeong, and M. M. N. Mannan, "Optimal hemodynamic response model for functional near-infrared spectroscopy," Front Behav Neurosci, vol. 9, Jun. 2015.

[7] E. E. Vidal-Rosas et al., "Reduced-order modeling of light transport in tissue for real-time monitoring of brain hemodynamics using diffuse optical tomography," J Biomed Opt, vol. 19, no. 2, p. 26008, Feb. 2014.

[8] I. W. Selesnick, H. L. Graber, D. S. Pfeil, and R. L. Barbour, "Simultaneous Low-Pass Filtering and Total Variation Denoising," IEEE Transactions on Signal Processing, vol. 62, no. 5, pp. 1109–1124, Mar. 2014.

[9] M. A. Kamran and K.-S. Hong, "Reduction of physiological effects in fNIRS waveforms for efficient brain-state decoding," Neurosci. Lett., vol. 580, pp. 130–136, Sep. 2014.

[10] N. Hemmati Berivanlou, S. K. Setarehdan, and H. Ahmadi Noubari, "Evoked hemodynamic response estimation using ensemble empirical mode decomposition based adaptive algorithm applied to dual channel functional near infrared spectroscopy (fNIRS)," Journal of Neuroscience Methods, vol. 224, pp. 13–25, Mar. 2014.

[11] C. Habermehl, J. Steinbrink, K.-R. Müller, and S. Haufe, "Optimizing the regularization for image reconstruction of cerebral diffuse optical tomography," J Biomed Opt, vol. 19, no. 9, p. 96006, Sep. 2014.

[12] V. C. Kavuri, Z.-J. Lin, F. Tian, and H. Liu, "Sparsity enhanced spatial resolution and depth localization in diffuse optical tomography," Biomed Opt Express, vol. 3, no. 5, pp. 943–957, Apr. 2012.

[13] C. Habermehl et al., "Somatosensory activation of two fingers can be discriminated with ultrahigh-density diffuse optical tomography," Neuroimage, vol. 59, no. 4, pp. 3201–3211, Feb. 2012.

[14] M. Aqil, K.-S. Hong, M.-Y. Jeong, and S. S. Ge, "Detection of event-related hemodynamic response to neuroactivation by dynamic modeling of brain activity," Neuroimage, vol. 63, no. 1, pp. 553–568, Oct. 2012.

[15] X.-S. Hu, K.-S. Hong, S. S. Ge, and M.-Y. Jeong, "Kalman estimator- and general linear model-based on-line brain activation mapping by near-infrared spectroscopy," Biomed Eng Online, vol. 9, p. 82, 2010.

[16] A. Bluestone, G. Abdoulaev, C. Schmitz, R. Barbour, and A. Hielscher, "Three-dimensional optical tomography of hemodynamics in the human head," Opt Express, vol. 9, no. 6, pp. 272–286, Sep. 2001.

[17] R. L. Barbour, H. L. Graber, J. Chang, S.-L. S. Barbour, P. C. Koo, and R. Aronson, "MRI-Guided Optical Tomography: Prospects and Computation for a New Imaging Method," IEEE Comput. Sci. Eng., vol. 2, no. 4, pp. 63–77, Dec. 1995.

Traumatic Brain Injury (TBI)

TBI affects nearly 2.5M individual's annually (CDC). fNIRS is a versatile approach to explore the breadth of challenges resulting from this varied injury. Whether it involves rehabilitation or acute evaluation, fNIRS is logical choice as a leading investigative tool.

[1] I. Helmich, A. Berger, and H. Lausberg, "Neural Control of Posture in Individuals with Persisting Postconcussion Symptoms," Med Sci Sports Exerc, Jul. 2016.

[2] I. Helmich, R. S. Saluja, H. Lausberg, M. Kempe, P. Furley, A. Berger, J.-K. Chen, and A. Ptito, "Persistent Postconcussive Symptoms Are Accompanied by Decreased Functional Brain Oxygenation," J Neuropsychiatry Clin Neurosci, vol. 27, no. 4, pp. 287–298, 2015.

Please visit: http://www.ninds.nih.gov/disorders/tbi/tbi.htm, for latest updates on NINDS funding priorities and resources for TBI investigations. Also see http://inclinicaltrials.com/traumatic-brain-injury/01789164.aspx, for ongoing clinical trials involving fNIRS technology.

Visual Stimulation

The intrinsic portability of the technology allied with the performance in the presence of movements makes fNIRS a promising tool to explore particular visual stimulation studies, for example concerning age-related hemodynamic changes, alcohol ingestion and, specially, brain monitoring during sleep.

[1] N. H. Kashou and B. M. Giacherio, "Stimulus and optode placement effects on functional near-infrared spectroscopy of visual cortex," Neurophotonics, vol. 3, no. 2, p. 25005, Apr. 2016.

[2] L.-C. Chen, P. Sandmann, J. D. Thorne, M. G. Bleichner, and S. Debener, "Cross-Modal Functional Reorganization of Visual and Auditory Cortex in Adult Cochlear Implant Users Identified with fNIRS," Neural Plast, vol. 2016, 2016.

[3] A. D. Zaidi et al., "Simultaneous epidural functional near-infrared spectroscopy and cortical electrophysiology as a tool for studying local neurovascular coupling in primates," Neuroimage, vol. 120, pp. 394–399, Oct. 2015.

[4] E. Maggioni et al., "Investigation of negative BOLD responses in human brain through NIRS technique. A visual stimulation study," NeuroImage, vol. 108, pp. 410–422, Mar. 2015.

[5] X. Liu and K. S. Hong, "fNIRS based color detection from human visual cortex," in Society of Instrument and Control Engineers of Japan (SICE), 2015 54th Annual Conference of the, 2015, pp. 1156–1161.

[6] L.-C. Chen, P. Sandmann, J. D. Thorne, C. S. Herrmann, and S. Debener, "Association of Concurrent fNIRS and EEG Signatures in Response to Auditory and Visual Stimuli," Brain Topogr, vol. 28, no. 5, pp. 710–725, Sep. 2015.

[7] K.-S. Hong and H.-D. Nguyen, “State-space models of impulse hemodynamic responses over motor, somatosensory, and visual cortices,” Biomed Opt Express, vol. 5, no. 6, pp. 1778–1798, May 2014.

[8] C.-H. Chen, M.-S. Ho, K.-K. Shyu, K.-C. Hsu, K.-W. Wang, and P.-L. Lee, “A noninvasive brain computer interface using visually-induced near-infrared spectroscopy responses,” Neuroscience Letters, vol. 580, pp. 22–26, Sep. 2014.

[9] E. Maggioni et al., “Coupling of fMRI and NIRS measurements in the study of negative BOLD response to intermittent photic stimulation,” in 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2013, pp. 1378–1381.

[10] G. R. Wylie et al., “Using co-variations in the Hb signal to detect visual activation: A near infrared spectroscopic imaging study,” NeuroImage, vol. 47, no. 2, pp. 473–481, Aug. 2009.