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Introduction to the Issue on fMRI Analysis for Human Brain Mapping

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Functional magnetic resonance imaging (fMRI), one of the most recently developed forms of neuroimaging technology, allows noninvasive assessment of brain activity and has been aptly called “our window into the human brain”. By enabling researchers to study temporal and spatial changes in both the healthy and the diseased brain as a function of various stimuli, fMRI has contributed significantly to our understanding of the brain, and its study has been one of the most active areas of research. The study of fMRI data is highly interdisciplinary due to its unique nature and particular challenges. Between the two main groups—the developers of the technology and the ultimate end users—there is a major shift and increasing recognition of the role signal processing plays for extracting, processing, analyzing and modeling fMRI data for human brain mapping. As a result, fMRI analysis for human brain mapping has been gaining importance and momentum within the signal processing community. This special issue aims to underline this major current trend and bring together a diverse but complementary set of contributions to address the current brain mapping challenges and the solutions where signal processing plays an important role.

The selected papers in this special issue clearly indicate the increasingly important role of signal processing in fMRI analysis for human brain mapping and also underline important challenges in the area. The selected papers present significant contributions in three primary areas: data acquisition and preprocessing; brain activity detection and pattern analysis; and brain functional connectivity.

Data Acquisition and Preprocessing

Papers in this area address the practical concerns in data acquisition and preprocessing. The paper by Tieng *et al.* presents a methodology for determining accurate coil sensitivity profiles for faster, also with fewer artifacts, MRI image reconstruction. Pre-whitening of fMRI data, a widely performed fMRI preprocessing, is sensitive to the accuracy of the autocorrelation estimates. The paper by Lenoski *et al.* proposes an evaluation framework for testing the accuracy of today's state-of-the-art autocorrelation estimates. Simultaneous EEG and fMRI is emerging as a powerful tool for brain function study. The paper by Mahadevan *et al.* describes a new discrete Hermite transform method for BCG artifact removal from an EEG signal recorded in a MR scanner.

Activity Detection and Pattern Analysis

The majority of fMRI studies in brain mapping focus on detecting experimentally induced or spontaneous changes in brain activity and enabling better analysis of brain activity patterns, with numerous applications in both clinical and fundamental neuroscience.

In this context, accurate registration of an fMRI and a reference high-resolution anatomical image and noise reduction are critical initial steps for brain activity detection. The paper by Gholipour *et al.* presents an enhanced multistage mutual information-based constrained deformable registration technique and a systematic *in vivo* validation framework. The paper by Liu *et al.*, on the other hand, studies both structured and unstructured noise in fMRI and presents a novel unsupervised noise-reduction method using canonical correlation analysis (CCA). The paper by Atkinson *et al.* specifically targets small regions of low CNR BOLD signals and presents a blind estimation scheme to detect small regions of low CNR activation more robustly, and the paper by Rydell *et al.* shows that combining different similarity measures using bilateral adaptive filtering increases the accuracy of activity detection.

The papers in this area also explore new approaches in an effort to improve activity detection performance, address the inter-subject variability issue, and allow for better interpretation of activation maps. Instead of controlling type I error rate, Van De Ville and Unser propose adapting the false discovery rate principle to the Wavelet-Based Statistical Parametric Mapping framework in obtaining parametric brain activity maps. The paper by Uthama *et al.* presents a novel spherical-harmonic feature based framework for analyzing fMRI spatial activation patterns across groups. The paper by Malin Aberg *et al.* proposes a novel evolutionary classification scheme for brain state discrimination and can produce multiclass voxel relevance maps. The paper by Ciuciu *et al.* proposes applying scaling and multifractal analyses to EVI fMRI data. The results strongly support the presence of scaling parameter changes in fMRI data between ongoing and evoked brain activity. It has become increasingly important to integrate fMRI with EEG measures to obtain a better understanding of the brain processes. The paper by Gonçalves *et al.* investigates the inter-subject variability of the BOLD signal using hierarchical clustering and the co-registered EEG is used to provide an interpretation to the derived clusters.

Almost all of the papers in our issue use conventional single-echo fMRI data while the development of parallel imaging technology has now made possible the collection of multi-echo fMRI data. The paper by Buur *et al.* introduces the notion of multi-echo fMRI data as a multi-channel signal, and examines three different source extraction approaches for improved estimates of task-related BOLD activation from the multi-echo data.

Functional Connectivity

Papers in this category contribute to study effective brain connectivity, defined as the neural influence that one brain region exerts over another. This topic is of critical importance for the understanding and assessment of brain function in normal and disease states. The paper by Mader *et al.* investigates directed partial correlation for inferring brain interaction network structure and the paper by Ma *et al.* adopts a binary representation for block-designed fMRI data, and proposes applying Probabilistic Boolean Networks for modeling brain connectivity. Another key research problem is the fusion of data from two or more imaging modalities for the identification of interacting brain regions. The paper by Franco *et al.* uses the joint independent component analysis (ICA) approach for the simultaneous determination of white and gray matter connectivity by examining both resting state FMRI and DTI. In another paper, Correa *et al.* present multimodal CCA to identify linear associations between modalities such as fMRI and EEG, and fMRI and structural MRI. The advantages and limitations of the multimodal CCA and joint-ICA fusion schemes are discussed.

The papers selected in this special issue, we believe, provide an overview of the state-of-art in the exciting and fruitful field of signal processing and modeling of brain fMRI. We hope that this collection will help identify the important issues in fMRI analysis and the key challenges to the signal processing community to help with the growth of this promising field. We thank the authors for their outstanding contributions and the reviewers for their thoughtful comments. We are also grateful to Dr. Lee Swindlehurst, the Editor-in-Chief, for his support of the project and to Jayne Huber for her diligent work and patience when putting together the special issue.

Biographies

Tülay Adali received the Ph.D. degree in electrical engineering from North Carolina State University, Raleigh, in 1992

She joined the faculty at the University of Maryland Baltimore County (UMBC), Baltimore, in 1992, where she is currently a Professor in the Department of Computer Science and Electrical Engineering. She has held visiting positions at the Technical University of Denmark, Lyngby, Denmark, the Katholieke Universiteit, Leuven, Belgium, the University of Campinas, Brazil, and École Supérieure de Physique et de Chimie Industrielles, Paris, France. Her research interests are in the areas of statistical signal processing, machine learning for signal processing, biomedical data analysis (functional MRI, MRI, PET, CR, ECG, and EEG), bioinformatics, and signal processing for optical communications.

Prof. Adali assisted in the organization of a number of international conferences and workshops, including the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), the IEEE International Workshop on Neural Networks for Signal Processing (NNSP), and the IEEE International Workshop on Machine Learning for Signal Processing (MLSP). She was the General Co-Chair of NNSP (2001–2003); the Technical Chair of MLSP (2004–2006); the Publicity Chair of ICASSP (2000 and 2005); and the Publications Co-Chair of ICASSP 2008. She is currently the Technical Chair of the 2008 MLSP and Program Co-Chair of the 2008 Workshop on Cognitive Information Processing and the 2009 ICA

Conference. She Chaired the Signal Processing Society (SPS) Machine Learning for Signal Processing Technical Committee (2003–2005); is a Member of the SPS Conference Board (1998–2006) and of the Bio Imaging and Signal Processing Technical Committee (2004–2007); and is an Associate Editor of the IEEE Transactions on Signal Processing (2003–2006). She is currently a Member of the Machine Learning for Signal Processing Technical Committee and an Associate Editor for the IEEE Transactions on Biomedical Engineering and *Signal Processing*. She is the recipient of a 1997 National Science Foundation (NSF) CAREER Award with more recent support from the National Institutes of Health, NSF, NASA, the U.S. Army, and industry. She is a Fellow of the IEEE and the AIMBE.

Z. Jane Wang (M'02) received the B.Sc. degree (with highest honors) from Tsinghua University, Beijing, China, in 1996, and the M.Sc. and Ph.D. degrees from the University of Connecticut, Storrs, in 2000 and 2002, respectively, all in electrical engineering.

She was a Research Associate in the Electrical and Computer Engineering Department, University of Maryland, College Park. Since August 2004, she has been an Assistant Professor with the Department Electrical and Computer Engineering, University of British Columbia (UBC), Vancouver, BC, Canada. Her research interests are in the broad areas of statistical signal processing, with applications to multimedia security and biomedical signal modeling and imaging.

Dr. Wang co-received the EURASIP Best Paper Award in 2004 and the IEEE Signal Processing Society (SPS) Best Paper Award in 2005. She is an Associate Editor of the *EURASIP Journal on Bioinformatics and Systems Biology* and the IEEE Transactions on Multimedia, and a member of the IEEE SPS Bio-imaging Signal Processing Technical Committee.

Martin J. McKeown graduated in engineering physics (summa cum laude) from McMaster University, Hamilton, ON, Canada, in 1986, and subsequently received the M.D. degree from the University of Toronto, Toronto, ON, in 1990.

From 1990 to 1994, he specialized in neurology at the University of Western Ontario, and later did a fellowship in clinical electrophysiology. From 1995 to 1998, he was a Research Associate at the Computational Neurobiology Lab, Salk Institute for Biology Studies, San Diego, CA. From 1998 to 2003, he was an Assistant Professor of Medicine at Duke University, a Core Faculty at Duke's Brain Research and Analysis Center, as well as an Adjunct Professor in Biomedical Engineering and Duke's Center for Neural Analysis. He is currently an Associate Professor of Medicine (Neurology) and Faculty Member of the Pacific Parkinson's Research Center, and the Brain Research Centre at the University of British Columbia, Vancouver, BC, Canada. His current work includes electrophysiology and fMRI as it pertains to patients with movement disorders. In addition to research, he trains physicians in neurology and treats patients with movement disorders, such as Parkinson's disease. He is Board Certified in neurology in Canada and the U.S., and has been an examiner for the U.S. Neurology Board certification.

Philippe Ciuciu was born in France in 1973. He graduated from the École Supérieure d'Informatique Électronique Automatique, Paris, France, in 1996 and received the D.E.A. and Ph.D. degrees in signal processing from the Université de Paris-sud, Orsay, France, in 1996 and 2000, respectively.

In November 2000, he joined the fMRI Signal Processing Group, Service Hospitalier Frédéric Joliot (CEA, Life Science Division, Medical Research Department), Orsay, as a Postdoctoral Fellow. Since November 2001, he has been a permanent Research Scientist at CEA, Gif-sur-Yvette, France. In 2007, he moved to Neuro Spin, an ultra-high magnetic field Neurospin center in the LNAO Laboratory. Currently, he is a Principal Investigator of the Neurodynamics Program, in collaboration with A. Kleinschmidt at the Cognitive Neuroimaging Unit. His research is focused on the application of statistical methods (e.g., Bayesian inference, model selection), stochastic algorithms (MCMC), and wavelet-based regularized approaches to functional brain imaging (fMRI) and to parallel MRI reconstruction (OPTIMED/ANR project).

Lars Kai Hansen is a Professor of digital signal processing at the Technical University of Denmark, Lyngby. He is head of the THOR Center for Neuroinformatics and director of the Intelligent Sound project. His research concerns machine learning with applications in biomedicine and digital media, and is published in more than 200 papers and book chapters.

Andrzej Cichocki received the M.Sc. (Hons.), Ph.D., and Dr. Sc. (Habilitation) degrees, all in electrical engineering, from Warsaw University of Technology, Poland.

Since 1972, he has been with the Institute of Theory of Electrical Engineering, Measurement and Information Systems, Faculty of Electrical Engineering, Warsaw University of Technology, where he became a Full Professor in 1995. He spent several years at the University of Erlangen-Nuerenberg, Germany, as the Chair of Applied and Theoretical Electrical Engineering (directed by Prof. R. Unbehauen), as an Alexander-von-Humboldt Research Fellow, and Guest Professor. In 1995-1997, he was a Team Leader of the Laboratory for Artificial Brain Systems at Frontier Research Program RIKEN (Japan), in the Brain Information Processing Group (directed by Prof. S. Amari). He is currently the head of the Laboratory for Advanced Brain Signal Processing at RIKEN Brain Science Institute (Japan) in the Technology Development Group. He is the co-author of more than 250 scientific papers and four monographs (two of them translated to Chinese): *Adaptive Blind Signal and Image Processing* (New York: Wiley, 2003, revised edition), *Nonnegative Matrix and Tensor Factorizations and Beyond* (New York: Wiley, 2009), *CMOS Switched-Capacitor and Continuous-Time Integrated Circuits and Systems* (Berlin: Springer-Verlag, 1989), and *Neural Networks for Optimizations and Signal Processing* (New York: Teubner-Wiley, 1994). He is the Editor-in-Chief of the international journal *Computational Intelligence and Neuroscience*.

Vince D. Calhoun (S'88–M'02–SM'05) received the Bachelor's degree in electrical engineering from the University of Kansas, Lawrence, in 1991, the Master's degrees in biomedical engineering and information systems from John's Hopkins University, Baltimore, MD, in 1993 and 1996, respectively, and the Ph.D. degree in electrical engineering from the University of Maryland Baltimore County, Baltimore, in 2002.

He was a Senior Research Engineer at the Psychiatric Neuro-Imaging Laboratory, John's Hopkins, from 1993 until 2002. He then became the Director of Medical Image Analysis at the Olin Neuropsychiatry Research Center and an Associate Professor at Yale University. He is currently Director of Image Analysis and MR Research at the Mind Research Network and is an Associate Professor in the Department of Electrical and Computer Engineering, Neurosciences, and Computer Science at the University of New Mexico, Albuquerque. He is

the author of more than 80 full journal articles and over 200 technical reports, abstracts, and conference proceedings. Much of his career has been spent on the development of data-driven approaches for the analysis of functional magnetic resonance imaging (fMRI) data. He has multiple NSF and NIH grants on the incorporation of prior information into independent component analysis (ICA) for fMRI, data fusion of multimodal imaging and genetics data, and the identification of biomarkers for disease. He has participated in multiple NIH study sections.

Dr. Calhoun is a Senior Member of the Organization for Human Brain Mapping and the International Society for Magnetic Resonance in Medicine. He has worked in the organization of workshops at conferences including the Society of Biological Psychiatry (SOBP) and the International Conference Of Independent Component Analysis And Blind Source Separation (ICA). He is currently serving on the IEEE Machine Learning for Signal Processing (MLSP) Technical Committee and has previously served as the General Chair of the 2005 meeting. He is a reviewer for a number of international journals and is on the Editorial Board of the *Human Brain Mapping* and *Neuroimage* journals and an Associate Editor for the IEEE Signal Processing Letters and the *International Journal of Computational Intelligence and Neuroscience*.