

Alberto Greco · Gaetano Valenza
Enzo Pasquale Scilingo

Advances in Electrodermal Activity Processing with Applications for Mental Health

From Heuristic Methods to Convex
Optimization



Springer

Advances in Electrodermal Activity Processing with Applications for Mental Health

Alberto Greco • Gaetano Valenza
Enzo Pasquale Scilingo

Advances in Electrodermal Activity Processing with Applications for Mental Health

From Heuristic Methods to Convex
Optimization

Alberto Greco
Department of Information Engineering
Bioengineering and Robotics
Research Center 'E Piaggio'
University of Pisa
Pisa, Italy

Gaetano Valenza
Department of Information Engineering
Bioengineering and Robotics
Research Center 'E Piaggio'
University of Pisa
Pisa, Italy

Enzo Pasquale Scilingo
Department of Information Engineering
Bioengineering and Robotics
Research Center 'E Piaggio'
University of Pisa
Pisa, Italy

ISBN 978-3-319-46704-7 ISBN 978-3-319-46705-4 (eBook)
DOI 10.1007/978-3-319-46705-4

Library of Congress Control Number: 2016952862

© Springer International Publishing AG 2016

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

This book presents a critical review of methodological studies for the analysis of the electrodermal activity (EDA), one of the most powerful noninvasive peripheral measures of the autonomic nervous system (ANS) neural pathway. Through the book, the author leads the reader from a thorough description of electrodermal physiological phenomena to an advanced introduction and discussion of recommended techniques for correct data collection and effective data analysis. Several experimental setups are also presented.

Although the EDA signal is fairly easy to acquire and very informative, powerful methodologies and efficient models are required to make meaningful inferences on the dynamics at the central nervous system level. The book introduces and emphasizes a novel computational model for EDA analysis that I have personally promoted and coauthored. The method relies on rigorous mathematical techniques, such as convex optimization, to provide an effective window on the ANS dynamics, and it has been successfully applied in several experimental scenarios. EDA is a source of many sensitive psychophysiological markers and it finds application in several fields of research, such as psychology and medicine, as a viable indicator in emotion assessment and pathological mood state recognition. Remarkably, the book presents several experimental applications exploring different sensory channels for emotion stimulation in both healthy subjects and bipolar patients with very promising results.

I am confident the reader will find useful information on proper characterization of EDA dynamics and how this can be applied to the rising fields of affective computing and psychophysiology. The high technical content makes the book attractive to anyone interested in signal processing, statistics, applied mathematics, and physics.

The book is a valuable reference for active research scientists and postgraduate students interested in methods at the interface of bioengineering and statistics. I expect that this book will stimulate and encourage the use of such methods in different fields of applied science.

Colchester, UK
August 2016

Dr. Luca Citi

Preface

Electrodermal activity (EDA) can be considered one of the most common perceptual channel, of the autonomic nervous system (ANS) dynamics and manifests itself as changes in electrical properties of the skin. Several previous studies have shown how EDA can be a very informative biomedical sign with high discriminant power between different psychophysiological states, although in this case many methodological issues arise. This book fervently shows how to retrieve much reliable information from EDA, to investigate also the assessment of emotional responses in healthy subjects and patients with pathological mood/mental states. Throughout the chapters, in-depth methodological and applicative studies involving EDA are described, including a critical review on the current state of the art. Since continuous deconvolution analysis (CDA) has been recognized as one of the mostly used methods for EDA analysis, we first show how to apply this model to discern different affective states in healthy volunteers. Emotions were evoked using multimodal standardized sets of pictures, sounds, caresses, and smells. Valence and arousal levels of such emotions were identified as the principal dimensions of the affective responses. The achieved results are consistent with the hypothesis that it is possible to objectively study ANS dynamics involved in the emotional processing by properly processing the EDA.

Furthermore, this book reports on a novel computational model for the EDA analysis based on convex optimization methods. This model, hereinafter called *cvxEDA*, describes the EDA as a sum of the phasic component, the tonic component, and an additive white Gaussian noise term incorporating prediction errors, as well as measurement errors and artifacts. *CvxEDA* is physiologically inspired and overcomes the limitations of the heuristic solutions and post-processing steps of the conventional approach. It is based on a rigorous methodology grounded on Bayesian statistics, mathematical convex optimization, and sparsity. Building on our previous CDA-based experimental results, outcomes of *cvxEDA* often demonstrate higher accuracy than CDA while discerning elicited emotional states in healthy subjects. When applied to EDA from psychiatric patients suffering from bipolar

disorder, it is shown how EDA significantly changes according to different mood states. This also allows using EDA phasic and tonic components as suitable markers for discriminating pathological mood states in bipolar patients.

Pisa, Italy

Alberto Greco
Gaetano Valenza
Enzo Pasquale Scilingo

Acknowledgments

We would like to express our deepest and sincere gratitude to all the people who contributed to data acquisition and analysis: Dr. Antonio Lanatá, Dr. Andrea Guidi, Dr. Mimma Nardelli, Dr. Matteo Bianchi, Prof. Claudio Gentili, Dr. Nicola Vanello. A special mention to Dr. Luca Citi for his fundamental contribution to our research and for his foreword.

Contents

1	Electrodermal Phenomena and Recording Techniques	1
1.1	Electrodermal Activity and Skin Conductance	1
1.2	Anatomy of the Skin	2
1.3	Anatomy of Sweat Glands	4
1.4	Physiology of the Electrodermal System	5
1.4.1	Mechanisms of the Electrodermal Electrophysiological Response	7
1.4.2	Genesis of the Electrodermal Response	8
1.5	Recording Systems	9
1.5.1	Measurement Sites	11
1.6	Exemplary Electrodermal Activity Monitoring Devices	11
1.6.1	DC Source Front-End	12
1.6.2	AC Source Front-End	13
1.6.3	Remote DC Devices	14
1.6.4	Wearable DC Devices	15
1.6.5	Multi-Frequency Sensorized Glove	16
2	Modeling for the Analysis of the EDA	19
2.1	Mathematical Models of the EDA: An Overview	19
2.2	EDA Analysis	21
2.2.1	Conventional Analysis	21
2.2.2	Model-Based Approach	22
2.3	CDA: Continuous Deconvolution Analysis	23
2.3.1	Preprocessing	23
2.3.2	EDA Deconvolution Analysis	24
2.3.3	Optimization	25
2.4	CvxEDA: A Convex Optimization Approach to Electrodermal Activity Processing	25
2.4.1	Convex Optimization	25
2.4.2	Model Assumptions	26

2.4.3	Observation Model	27
2.4.4	Maximum a Posteriori Estimation	28
2.5	Feature Extraction	31
2.5.1	Time Domain	31
2.5.2	Frequency Domain	32
3	Evaluation of CDA and CvxEDA Models	35
3.1	Synthetic Data	36
3.2	Experiment 1: Maximal Expiration Task	36
3.3	Experiment 2: Visual Affective Stimuli	37
3.4	EDA Processing and Analysis	37
3.5	Experimental Evaluation Results	38
3.5.1	Results on Synthetic Data	39
3.5.2	Experiment 1 Results	41
3.5.3	Experiment 2 Results	42
4	Emotions and Mood States: Modeling, Elicitation, and Recognition	45
4.1	Theory of Emotions	45
4.2	Modeling Emotions	46
4.3	Autonomic Nervous System Correlates of Emotions	48
4.4	Affective Computing	50
4.5	Multi-Sensory Elicitation	52
4.6	Emotions and Mood Disorders: Bipolar Disorder	53
5	Experimental Applications on Multi-Sensory Affective Stimulation...	55
5.1	Multi-Sensory Experimental Applications	57
5.2	Classification Procedure	58
5.2.1	Paired Within-Rank K-NN Classifier	58
5.2.2	Support Vector Machine	60
5.3	Affective Visual Elicitation	60
5.3.1	Experimental Protocol of Affective Visual Elicitation	61
5.3.2	Classification of Visual Arousal and Valence Levels	62
5.4	Affective Sound Elicitation	63
5.4.1	Subject Recruitment, Experimental Protocol and Acquisition Set-Up	64
5.4.2	Feature Extraction and Statistical Analysis	64
5.4.3	Experimental Results	67
5.5	Affective Touch Elicitation	68
5.5.1	A Device for Caress-Like Haptic Stimuli	70
5.5.2	Subject Recruitment, Experimental Protocol and Acquisition Set-Up	72
5.5.3	Feature Extraction, Performance Metrics, and Statistical Analysis	74
5.5.4	Statistical Results of the Self Assessment Questionnaire	75
5.5.5	Experimental Results of Tactile Stimulation	76

5.6	Affective Olfactory Elicitation	83
5.6.1	Subject Recruitment, Experimental Protocol and Acquisition Set-Up of the Olfactory Stimulation	88
5.6.2	Feature Extraction and Statistical Analysis	90
5.6.3	Statistical Analysis on Self-Assessment Questionnaire Scores	90
5.6.4	Statistical Analysis and Classification of Olfactory Valence Levels	91
5.6.5	Dataset Reduction and Gender Analysis	92
5.7	Assessment of Mood States in Bipolar Patients Using EDA	93
5.7.1	Patient Recruitment and Experimental Protocol	94
5.7.2	Experimental Results	97
5.8	Changing Source Oscillations of Skin Admittance: A Study in the Frequency Domain with Application on Emotion Recognition	103
5.8.1	Experimental Protocol	104
5.8.2	EDA Analysis and Classification Procedure	106
5.8.3	Classification Results	107
6	Conclusions	111
6.1	Future Challenges	120
	Bibliography	123

Acronyms and Symbols

The following table shows the most used and important acronyms.

Statement	Acronym
Autonomic nervous system	ANS
Central nervous system	CNS
Electrodermal activity	EDA
Electrodermal response	EDR
Electrodermal level	EDL
Skin conductance	SC
Skin conductance response	SCR
Skin conductance level	SCL
Non specific skin conductance response	NsSCR
Heart rate variability	HRV
International Affective Picture System	IAPS
Circumplex model of affect	CMA
International Affective Digital Sounds	IADS
Continuous deconvolution analysis	CDA
Signal-to-noise ratio	SNR
Finite impulse response	FIR
Infinite impulse response	IIR
Impulse response function	IRF
Auto-regressive moving average	ARMA
Auto-regressive	AR
Moving average	MA
Area under the curve	AUC
Respiratory volume	RV
Respiration activity	RSP
Skin temperature	ST
Pupil diameter	PD

Impedance cardiogram	ICG
Heart sound	HS
Linear discriminant analysis	LDA
Artificial neural network	ANN
Support vector machine	SVM
Canonical correlation analysis	CCA
Stepwise discriminant analysis	SDA
Classification and regression tree	CART
Quadratic discriminant analysis	QDC

Introduction

This book is intended to provide an exhaustive description of the electrodermal activity (EDA), from a deep insight onto the physiological foundations to ad hoc algorithmic methods to analyze it. Expected audience ranges from researchers with expertise in signal processing who would like to approach EDA analysis for their first time, to experienced EDA researchers aimed to take into account recent advances in EDA sparse modeling. Proper links to MATLAB software for EDA analysis are also provided (see Chap. 2). Our principal aim is to show how EDA can be at the center of breakthrough investigations involving the autonomic nervous system (ANS) activity, being also a source of reliable and effective biomarkers of healthy affective responses and pathological mood/mental states.

EDA manifests itself as a change in electrical properties of the skin, i.e., skin conductance (SC). There are two main components of EDA having different time scales and relationships with exogenous stimuli: the tonic and phasic components.

In the first part of the book, we describe the electrodermal physiological phenomena underlying SC variations. Moreover, we include a critical review on the current state of the art concerning EDA application, analysis methods, and recording systems for both laboratory settings and ecological scenarios. The description of a recently proposed recording system which uses different frequencies for the demodulation of EDA components is also emphasized. Importantly, despite the widespread use of EDA device-related measurements, the actual biological phenomena underlying EDA (i.e., skin sympathetic nerve activity) remain unknown. Therefore, in the last decades, several mathematical models were developed to overcome this limitation, trying to investigate on how ANS activity regulates the EDA dynamics. In this book, we rely on the classical model describing SC as the sum of three terms: the phasic component, the tonic component, and an additive white Gaussian noise term incorporating model prediction errors as well as measurement errors and artifacts.

In this part of the book, we also emphasize a recently proposed, physiologically inspired EDA model based on a rigorous mathematical approach, grounded on Bayesian statistics, convex optimization, and sparsity. The phasic component is seen as the result of a convolution between a bioinspired bi-exponential impulse

response function (IRF) and a sparse signal representing the sudomotor nerve activity, which is part of the ANS. The IRF is modeled as an IIR filter allowing a much more compact and non-banded matrix representation increasing the accuracy and reducing the computational cost. Unlike previous algorithms in the literature, this model incorporates the intrinsic physiological characteristics of EDA without necessarily resorting to heuristics and ad hoc solutions, thanks to the presence and definition of prior probabilities for the phasic and tonic signals. Results were compared to those obtained through the continuous deconvolution analysis (CDA) model [1], a method that performs a deterministic inversion of the peripheral model. The proposed method showed good performance confirming a promising applicability in the field of affective computing as well as of mental health.

In the second part of the book, we report on several EDA application scenarios, especially related to two specific research fields: emotion recognition and assessment of mood/mental disorder. Indeed, emotions and mental disorders are strictly and intrinsically interrelated; therefore, when emotions are dysregulated, mental health is not guaranteed. Affective experiences accompany all cognitive processes and social activities even in the case of psychopathologies [2, 3]. Moreover, prevalent theories affirm that the emotional processes can have primacy over cognition [4]. As an example, the regulation process of emotions is crucial in the occurrence and control of major depressive episodes, and some theoretical views of depression are based on emotion changes which have implications in the assessment, treatment, and prevention of the pathology [5]. Another well-known relationship between emotions and mental disorders regards anxiety [6] as well as brain damages of emotional processing areas and decision-making process [7].

In this part of the book, several experimental results gathered from testing EDA models to robustness to noise, ability to separate and identify exogenous stimuli, and capability of properly describing the activity of the autonomic nervous system in response to specific affective elicitation are reported in detail. Concerning the affective elicitation paradigm, we show exemplary applications of EDA modeling on data gathered from healthy subjects undergoing multimodal affective elicitation, where visual, auditory, olfactory, and tactile stimuli were investigated. Concerning the mental health scenario, EDA analysis was employed to assess patients with bipolar disorder [8–10], who experienced depressive and manic or hypomanic episodes. Data used for this study were acquired in the frame of a European collaborative project called PSYCHE (personalized monitoring systems for care in mental health) [8, 11].