

Human–Computer Interaction Series

Editors-in-chief

Desney Tan, Microsoft Research, USA

Jean Vanderdonckt, Université catholique de Louvain, Belgium

HCI is a multidisciplinary field focused on human aspects of the development of computer technology. As computer-based technology becomes increasingly pervasive – not just in developed countries, but worldwide – the need to take a human-centered approach in the design and development of this technology becomes ever more important. For roughly 30 years now, researchers and practitioners in computational and behavioral sciences have worked to identify theory and practice that influences the direction of these technologies, and this diverse work makes up the field of human-computer interaction. Broadly speaking it includes the study of what technology might be able to do for people and how people might interact with the technology. The HCI series publishes books that advance the science and technology of developing systems which are both effective and satisfying for people in a wide variety of contexts. Titles focus on theoretical perspectives (such as formal approaches drawn from a variety of behavioral sciences), practical approaches (such as the techniques for effectively integrating user needs in system development), and social issues (such as the determinants of utility, usability and acceptability).

Titles published within the Human–Computer Interaction Series are included in Thomson Reuters' Book Citation Index, The DBLP Computer Science Bibliography and The HCI Bibliography.

More information about this series at <http://www.springer.com/series/6033>

Fang Chen • Jianlong Zhou • Yang Wang
Kun Yu • Syed Z. Arshad • Ahmad Khawaji
Dan Conway

Robust Multimodal Cognitive Load Measurement

Fang Chen
National ICT Australia (NICTA)
Sydney, NSW
Australia

Jianlong Zhou
National ICT Australia (NICTA)
Sydney, NSW
Australia

Yang Wang
National ICT Australia (NICTA)
Sydney, NSW
Australia

Kun Yu
National ICT Australia (NICTA)
Sydney, NSW
Australia

Syed Z. Arshad
National ICT Australia (NICTA)
Sydney, NSW
Australia

Ahmad Khawaji
National ICT Australia (NICTA)
Sydney, NSW
Australia

Dan Conway
National ICT Australia (NICTA)
Sydney, NSW
Australia

ISSN 1571-5035 ISSN 978-3-319-31700-7 (electronic)
Human-Computer Interaction Series
ISBN 978-3-319-31698-7 ISBN 978-3-319-31700-7 (eBook)
DOI 10.1007/978-3-319-31700-7

Library of Congress Control Number: 2016937498

© Springer International Publishing Switzerland 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 Switzerland

Preface

The body of knowledge presented in this book is timely. As we enter the age of data, human capacities are increasingly the critical factor in determining the output of human-machine interactions. This has important implications not only in high reliability operations such as aviation, command and control and complicated industrial and commercial applications, but also in everyday device usage by the general population. In order to achieve optimal ‘human-in-the-loop’ system behaviour, it is therefore increasingly important to understand and adapt to the constraints of human cognitive abilities.

The research presented herein is the result of a unique combination of people and circumstances. A research group within NICTA had been carrying out research into interface technologies and for some years, producing both basic research and engineered applications. The team had a track record in the investigation of speech, linguistic features, gestures and then later physiological signals such as Galvanic Skin Response (GSR), eye-based signals, pen gestures and electroencephalography (EEG), all in the context of developing cutting-edge user interfaces. These investigations then evolved into a research focus on the advantages of multimodal interfaces and how cognitive architectures, when linked with technology, can be leveraged to provide more efficient and responsive Human-Computer Interaction (HCI).

Sometime in late 2004, during a site visit to a traffic emergency response facility, a manager asked me the following question: ‘All my operators typically have multiple issues open that they are working on at any one time. When something dramatic and urgent occurs that requires immediate attention – who should I give the additional issue to?’

Armed with its previous experience, our team thus focused its attention on investigating and operationalizing the construct of cognitive load and its effect on user performance with the aim of providing robust, real-time quantification tools and methods. This work was then extended into the design of adaptive systems (both human and machine) that are able to compensate for the intersection of task demands and a user’s cognitive capacities. Answering these questions has involved a 10 year research campaign involving 13 staff, 16 PhD students, numerous other

researchers and along the way produced over 70 papers, four patent families (applied and granted in countries including the USA, Canada and Australia), finally culminating in this book.

A fundamental conceptual principle that emerged from this body of research is that the ability to observe and quantify the end-user through sophisticated data collection techniques enables systems to adapt to constantly changing work environments. This is achieved by learning about the intersection of multiple sources of variance such as the different characteristics of each feature evaluated for each task component and in each context. Furthermore, the data analytics expertise within the group allowed an unprecedented level of analysis of the complicated signals generated by both human behaviour and physiology.

It should be noted that the team that has carried out much of the research presented here is situated firmly within a data-driven approach and is at the vanguard of machine learning and algorithmic technologies, which manifests itself within this work in both methods and applications. Many analyses presented here are machine learning based, but are discussed in general terms, thus being accessible to those not familiar with the methods themselves. The text is aimed at researchers and engineers generally, including undergraduates in HCI, psychology and related fields. There is also an emphasis on practical problems and applied research, as a result of the ongoing mandate of our team to grapple with pressing issues in the real world.

This book reviews the current state of play in the literature as well as presents our own research into multimodal cognitive load measurement focusing on non-intrusive physiological and behavioural modalities, such as signals derived from the eye, GSR, speech, language, pen input, mouse movement as well as multimodal approaches. Factors which affect cognitive load measurement such as stress, trust and environmental factors such as screen illumination are also discussed. Furthermore, dynamic workload adjustment and real-time cognitive load measurement with data streaming are presented. Finally, typical application examples of cognitive load measurement are reviewed to show the feasibility and applicability of multimodal cognitive load measurement to situated applications. This is the first book to systematically introduce various computational methods for automatic and real-time cognitive load measurement and by doing so moves the practical application of cognitive load measurement from the domain of the computer scientist and psychologist to more general end-users ready for widespread implementation.

Whilst there is more work to be done in the field, the overwhelming message that should be taken away from this book is that many of the approaches outlined herein have now been validated and that useful and responsive measurement of human cognitive load is both achievable and an important factor in bringing about a more perfect union with our machines.

Sydney, NSW, Australia
January 2016

Dr. Fang Chen

Acknowledgements

There are many people who have contributed to the multimodal cognitive load measurement over the past 10 years in our group at National ICT Australia (NICTA). Our first thank is given to all staff and students who had worked on cognitive load measurement during the past years at NICTA, they are Julien Epps, Natalie Ruiz, Bo Yin, Eric Choi, Yu Shi, M. Asif Khawaja, Nargess Nourbakhsh, Pega Zarjam, Siyuan Chen, Sazzad Hussain, Tet Fei Yap, Phu Ngoc Le, Ronnie Taib, Benjamin Itzstein, Nicholas Cummins, Ling Luo, Ju Young Jung and many others. Without them, this book would not have been written.

We also thank many volunteer participants from universities such as UNSW, USYD and various NICTA groups who contributed their precious time for many different cognitive load measurement experiments conducted at NICTA. These people, in many instances, are students who are busy with their study and staff who have time pressure for their deliverables gave freely of their time and experiences thereby enabling us, as cognitive load researchers, to research this fascinating topic. Their great contribution makes our cognitive load measurement experiment successful.

We acknowledge our collaborators from around the world who have had various discussions and comments on our work.

Lastly, and most importantly, we would like to thank NICTA providing all kinds of support in the past years to make our research and experiments run smoothly and successfully.

Contents

Part I Preliminaries

1	Introduction	3
1.1	What Is Cognitive Load	4
1.2	Background	5
1.3	Multimodal Cognitive Load Measurement	6
1.4	Structure of the Book	8
	References	12
2	The State-of-The-Art	13
2.1	Working Memory and Cognitive Load	13
2.2	Subjective Measures	15
2.3	Performance Measures	16
2.4	Physiological Measures	18
2.5	Behavioral Measures	19
2.6	Estimating Load from Interactive Behavior	23
2.7	Measuring Different Types of Cognitive Load	24
2.8	Differences in Cognitive Load	25
2.8.1	Gender Differences in Cognitive Load	25
2.8.2	Age Differences in Cognitive Load	25
2.8.3	Static Graphics Versus Animated Graphics in Cognitive Load	26
2.9	Summary	27
	References	27
3	Theoretical Aspects of Multimodal Cognitive Load Measures	33
3.1	Load? What Load? Mental? Or Cognitive? Why Not Effort?	34
3.2	Mental Load in Human Performance	34

3.2.1	Mental Workload: The Early Years	35
3.2.2	Subjective Mental Workload Scales and Curve	38
3.2.3	Cognitive Workload and Physical Workload Redlines	39
3.3	Cognitive Load in Human Learning	40
3.3.1	Three Stages of CLT: The Additivity Hypothesis	42
3.3.2	Schema Acquisition and First-in Method	43
3.3.3	Modality Principle in CTML	44
3.3.4	Has Measuring Cognitive Load Been a Means to Advancing Theory?	45
3.3.5	Bridging Mental Workload and Cognitive Load Constructs	49
3.3.6	CLT Continues to Evolve	50
3.4	Multimodal Interaction and Cognitive Load	51
3.4.1	Multimodal Interaction and Robustness	51
3.4.2	Cognitive Load in Human Centred Design	55
3.4.3	Dual Task Methodology for Inducing Load	55
3.4.4	Workload Measurement in a Test and Evaluation Environment	56
3.4.5	Working Memory's Workload Capacity: Limited But Not Fixed	58
3.4.6	Load Effort Homeostasis (LEH) and Interpreting Cognitive Load	59
3.5	Multimodal Cognitive Load Measures (MCLM)	63
3.5.1	Framework for MCLM	63
3.5.2	MCLM and Cognitive Modelling	65
3.5.3	MCLM and Decision Making	65
3.5.4	MCLM and Trust Studies	66
3.6	Summary	66
	References	67

Part II Physiological Measurement

4	Eye-Based Measures	75
4.1	Pupillary Response for Cognitive Load Measurement	75
4.2	Cognitive Load Measurement Under Luminance Changes	77
4.2.1	Task Design	77
4.2.2	Participants and Apparatus	78
4.2.3	Subjective Ratings	78
4.3	Pupillary Response Features	79
4.4	Workload Classification	80
4.4.1	Feature Generation for Workload Classification	81
4.4.2	Feature Selection and Workload Classification	82
4.4.3	Results on Pupillary Response	84
4.5	Summary	84
	References	85

5	Galvanic Skin Response-Based Measures	87
5.1	Galvanic Skin Response for Cognitive Load Measurement	87
5.2	Cognitive Load Measurement in Arithmetic Tasks	88
5.2.1	Task Design	88
5.2.2	GSR Feature Extraction	89
5.2.3	Feature Analyses	91
5.3	Cognitive Load Measurement in Reading Tasks	93
5.3.1	Task Design	93
5.3.2	GSR Feature Extraction	94
5.3.3	Feature Analyses	94
5.4	Cognitive Load Classification in Arithmetic Tasks	95
5.4.1	Features for Workload Classification	95
5.4.2	Classification Results	96
5.5	Summary	97
	References	98

Part III Behavioural Measurement

6	Linguistic Feature-Based Measures	103
6.1	Linguistics	103
6.2	Cognitive Load Measurement With Non-Word Linguistics	104
6.3	Cognitive Load Measurement with Words	106
6.3.1	Word Count and Words per Sentence	106
6.3.2	Long Words	106
6.3.3	Positive and Negative Emotion Words	106
6.3.4	Swear Words	107
6.3.5	Cognitive Words	107
6.3.6	Perceptual Words	107
6.3.7	Inclusive Words	107
6.3.8	Achievement Words	108
6.3.9	Agreement and Disagreement Words	108
6.3.10	Certainty and Uncertainty Words	108
6.3.11	Summary of Measurements	108
6.4	Cognitive Load Measurement Based on Personal Pronouns	110
6.5	Language Complexity as Indices of Cognitive Load	111
6.5.1	Lexical Density	111
6.5.2	Complex Word Ratio	111
6.5.3	Gunning Fog Index	112
6.5.4	Flesch-Kincaid Grade	112
6.5.5	SMOG Grade	112
6.5.6	Summary of Language Measurements	113
6.6	Summary	113
	References	114

7	Speech Signal Based Measures	115
7.1	Basics of Speech	116
7.2	Cognitive Load Experiments	116
7.2.1	Reading Comprehension Experiment	116
7.2.2	Stroop Test	118
7.2.3	Reading Span Experiment	118
7.2.4	Time Constraint	119
7.2.5	Experiment Validation	120
7.3	Speech Features and Cognitive Load	120
7.3.1	Source-Based Features	121
7.3.2	Filter-Based Features	121
7.4	A Comparison of Features for Cognitive Load Classification	123
7.4.1	Pitch and Intensity Features	123
7.4.2	EGG Features	124
7.4.3	Glottal Flow Features	126
7.5	Cognitive Load Classification System via Speech	129
7.6	Summary	129
	References	130
8	Pen Input Based Measures	133
8.1	Writing Based Measures	133
8.2	Datasets for Writing-Based Cognitive Load Examination	135
8.2.1	CLTex Dataset	136
8.2.2	CLSkt Dataset	137
8.2.3	CLDgt Dataset	138
8.3	Stroke-, Substroke- and Point-Level Features	139
8.4	Cognitive Load Implications on Writing Shapes	141
8.5	Cognitive Load Classification System	143
8.6	Summary	144
	References	145
9	Mouse Based Measures	147
9.1	User Mouse Activity	147
9.2	Mouse Features for Cognitive Load Change Detection	148
9.2.1	Temporal Features	148
9.2.2	Spatial Features	151
9.3	Limitations of Mouse Feature Measurements	155
9.4	Mouse Interactivity in Multimodal Measures	156
9.5	Summary	156
	References	157
 Part IV Multimodal Measures and Affecting Factors		
10	Multimodal Measures and Data Fusion	161
10.1	Multimodal Measurement of Cognitive Load	161
10.2	An Abstract Model for Multimodal Assessment	162

10.3	Basketball Skills Training	164
10.4	Subjective Ratings and Performance Results	165
10.5	Individual Modalities	167
10.6	Multimodal Fusion	169
10.7	Summary	171
	References	171
11	Emotion and Cognitive Load	173
11.1	Emotional Arousal and Physiological Response	173
11.2	Cognitive Load Measurement with Emotional Arousal	174
11.2.1	Task Design	174
11.2.2	Pupillary Response Based Measurement	175
11.2.3	Skin Response Based Measurement	176
11.3	Cognitive Load Classification with Emotional Arousal	177
11.3.1	Cognitive Load Classification Based on Pupillary Response	178
11.3.2	Cognitive Load Classification Based on GSR	179
11.3.3	Cognitive Load Classification Based on the Fusion	180
11.4	Summary	182
	References	182
12	Stress and Cognitive Load	185
12.1	Stress and Galvanic Skin Response	185
12.2	Cognitive Load Measurement Under Stress Conditions	186
12.2.1	Task Design	186
12.2.2	Procedures	187
12.2.3	Subjective Ratings	188
12.3	GSR Features Under Stress Conditions	188
12.3.1	Mean GSR Under Stress Conditions	188
12.3.2	Peak Features Under Stress Conditions	190
12.4	Summary	193
	References	194
13	Trust and Cognitive Load	195
13.1	Definition of Trust	195
13.2	Related Work	196
13.2.1	Trust	196
13.2.2	Trust and Cognitive Load	197
13.3	Trust of Information and Cognitive Load	199
13.3.1	Task Design	199
13.3.2	Data Collection	201
13.4	Data Analyses	203
13.5	Analysis Results	204
13.5.1	Subjective Ratings of Mental Effort	204
13.5.2	Linguistic Analysis of Think-Aloud Speech	204

13.6 Interpersonal Trust and Cognitive Load 211

13.6.1 Task Design 211

13.6.2 Results 211

13.7 Summary 212

References 213

Part V Making Cognitive Load Measurement Accessible

14 Dynamic Cognitive Load Adjustments in a Feedback Loop 217

14.1 Dynamic Cognitive Load Adjustments 217

14.2 Dynamic Workload Adaptation Feedback Loop 218

14.2.1 Task Design 218

14.2.2 Procedures 219

14.3 GSR Features 220

14.3.1 Signal Processing 220

14.3.2 Feature Extraction 221

14.4 Cognitive Load Classification 222

14.4.1 Offline Cognitive Load Classifications 222

14.4.2 Online Cognitive Load Classifications 223

14.5 Dynamic Workload Adjustment 225

14.5.1 Adaptation Models 225

14.5.2 Performance Evaluation of Adaptation Models 226

14.6 Summary 227

References 227

15 Real-Time Cognitive Load Measurement:

Data Streaming Approach 229

15.1 Sliding Window Implementation 230

15.2 Streaming Mouse Activity Features 231

15.3 Lessons Learnt 232

15.4 Summary 234

References 234

16 Applications of Cognitive Load Measurement 235

16.1 User Interface Design 235

16.2 Emergency Management 238

16.3 Driving and Piloting 240

16.4 Education and Training 241

16.5 Other Applications 243

16.6 Future Applications 244

References 245

Part VI Conclusions

17 Cognitive Load Measurement in Perspective 251

References 254