Physiologically-Mediated Interaction between Children with Profound Disabilities and Their Environment

by

Stefanie Lup Mun Blain

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Rehabilitation Sciences
Graduate Department of Biomaterials and Biomedical Engineering
University of Toronto

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Abstract

This thesis explores the physiologically-mediated interactions between children with profound disabilities and their environment. Using a structure inspired by the musical theme and variation compositional form, the concept of using physiological signals to enrich person-environment interaction will be addressed in two themes. The first theme explores how children with profound disabilities can use their physiological signals to interact with their environment. The variations on this theme: 1) appraise the literature and establish that peripheral autonomic nervous system signals can be controlled by mental activities; 2) present an algorithm that classifies an individual’s mental state using patterns of electrodermal activity to an accuracy of over 80%, and; 3) discusses the challenges with and potential solutions to creating an physiologically-based interaction pathway for children with profound disabilities. The second
theme explores how physiological signals can be used to assess the effect of the environmental milieu on a child with profound disabilities. The variations on this theme: 1) demonstrate the effects of the built environment on the life activities of a severely disabled individual by developing and evaluating the effects of a custom-tailored computer access technology; 2) illustrate how the physiological signals of profoundly disabled children are influenced by their social environment by studying the effect of Therapeutic Clowns on children in a long-term rehabilitation setting; and 3) illustrate how differential physiological responses to sounds in the environmental milieu can be used to inform and improve voluntary physiologically-mediated person-environment interaction. The coda of the thesis presents a conceptual framework that has the potential to enrich the interaction between profoundly disabled children and their environment, using music generated from physiological signal patterns to modify their environmental milieu, constructs of personhood and their identity.
Dedication

To Xiao, Soloman, Gurpal, Krystal, Rachel, Jessica, Adam, Hope, Raquelle, Adin, Dominic, Tresor, Malaika, Joey, Joseph, Peter, and their families for inspiring me to undertake this work.

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# Table of Contents

Dedication ...................................................................................................................................... iv  

Acknowledgments ........................................................................................................................... v  

Table of Contents ........................................................................................................................... vi  

List of Tables ................................................................................................................................... xiii  

List of Figures .................................................................................................................................. xiv  

1 **Overture** .................................................................................................................................... 1  

1.1 Motivation ................................................................................................................................... 1  

1.1.1 Children with profound disabilities ...................................................................................... 1 

1.1.2 Person-environment interaction in disability ........................................................................ 2 

1.1.3 Physiologically-mediated person-environment interaction ................................................ 4 

1.2 Research Questions .................................................................................................................. 5  

1.3 Contributions ............................................................................................................................ 5 

1.4 Layout of Thesis ......................................................................................................................... 7  

**Theme 1** ..................................................................................................................................... 9  

2 **Theme 1 Variation 1** .................................................................................................................. 10  

2.1 Abstract ..................................................................................................................................... 11  

2.2 Introduction ............................................................................................................................... 11  

2.2.1 Current Access Pathways to Assistive Technologies .......................................................... 11  

2.3 Overview of Autonomic Signals ............................................................................................... 15  

2.3.1 Electrodermal Activity ......................................................................................................... 15  

2.3.2 Heart Rate ............................................................................................................................ 16  

2.3.3 Respiration Rate and Amplitude .......................................................................................... 17  

2.3.4 Fingertip Temperature ......................................................................................................... 17  

2.4 Operant Control of Peripheral Autonomic Functions .............................................................. 19
2.4.1 Biofeedback ................................................................. 19
2.4.2 Polygraphy ................................................................. 23
2.4.3 Mental Exercises ........................................................ 25

2.5 Discussion ......................................................................................... 27
2.5.1 Challenge 1: Slow Rate of Response .............................. 27
2.5.2 Challenge 2: Metabolic Noise ........................................ 28
2.5.3 Challenge 3: Pathological Change ................................. 29

2.6 Conclusion ......................................................................................... 30

3 Theme 1 Variation 2 ................................................................. 31
Assessing the Potential of Electrodermal Activity as an Alternative Access Pathway .......... 31
3.1 Abstract ......................................................................................... 32
3.2 Introduction ....................................................................................... 32
3.3 Methods ......................................................................................... 34
3.3.1 Design ....................................................................................... 34
3.3.2 Participants ............................................................................... 34
3.3.3 Measures ................................................................................... 34
3.3.4 Data Collection ......................................................................... 35
3.3.5 Feature Extraction .................................................................. 36
3.3.6 Classifier Design ....................................................................... 37

3.4 Results ......................................................................................... 42
3.4.1 Session 1 ............................................................................... 42
3.4.2 Session 2 ............................................................................... 43

3.5 Discussion ......................................................................................... 44
3.5.1 Physiological Basis .............................................................. 44
3.5.2 Individual Tuning ................................................................. 44
3.5.3 Effect of Seasonal and Biological Rhythms ....................... 45
### 3.5.4 Detection Times

3.5.5 EDA Signal Features

3.5.6 Limitations of Present Study

3.6 Conclusions

### 4 Theme 1 Variation 3

Challenges of Developing a Physiological Signal-Based Access Pathway for Children with Profound Disabilities

4.1 Abstract

4.2 Introduction

4.3 Participant

4.4 Challenge 1: Intra-subject variability of physiological signals

4.5 Challenge 2: Reliance on third-party interpretations of preference

4.6 Challenge 3: Learned Helplessness

4.7 Discussion

4.7.1 Challenge 1: Continually adapting baseline

4.7.2 Challenge 2: Routine, Space and Context

4.7.3 Challenge 3: Contingency awareness training

4.8 Conclusion

### 5 Theme 2 Variation 1: The Built Environment

5.1 Abstract

5.2 Introduction

5.2.1 Computer access for individuals with severe and multiple disabilities

5.2.2 The benefits of computer access

5.2.3 Barriers to computer access

5.3 Methods
5.3.1 Description of the participant ................................................................. 70
5.3.2 Finding an access site ............................................................................. 71
5.3.3 The software solution ........................................................................... 73
5.3.4 The physical setup ................................................................................ 74
5.4 Measurement ............................................................................................. 76
5.4.1 System and human factors ................................................................. 76
5.4.2 The Canadian Occupational Performance Measure (COPM) ............. 78
5.4.3 Frequency and type of computer usage .............................................. 79
5.4.4 Typing speed and accuracy ................................................................. 79
5.4.5 Semi-structured interview ................................................................. 79
5.5 Results ...................................................................................................... 80
5.5.1 System and human factors ................................................................. 80
5.5.2 The Canadian Occupational Performance Measure (COPM) ............. 80
5.5.3 Frequency and type of computer usage .............................................. 81
5.5.4 Typing speed and accuracy ................................................................. 81
5.5.5 Semi-structured interview ................................................................. 82
5.6 Discussion ............................................................................................... 82
5.6.1 Expanding communication ................................................................. 82
5.6.2 New opportunities for interpersonal interactions and relationships .... 83
5.6.3 Facilitating education, leisure and spiritual activities ....................... 84
5.6.4 Environmental factors ......................................................................... 85
5.6.5 Access development approach ......................................................... 86
5.6.6 Need for access research ................................................................... 86
5.6.7 Limitations ......................................................................................... 87
5.7 Conclusion .............................................................................................. 88
6 Theme 2 Variation 2: The Social Environment I................................................................. 89

Physiological and Emotional Responses of Disabled Children to Therapeutic Clowns: A Pilot Study ........................................................................................................... 89

6.1 Abstract........................................................................................................................ 90

6.2 Introduction.................................................................................................................. 90

6.3 Method......................................................................................................................... 94
  6.3.1 Setting and Design ................................................................................................. 94
  6.3.2 Participants ........................................................................................................... 94
  6.3.3 Intervention .......................................................................................................... 95
  6.3.4 Data Collection ..................................................................................................... 95
  6.3.5 Measures ............................................................................................................... 96

6.4 Analysis and Results ................................................................................................. 98
  6.4.1 Physiological Signals ............................................................................................ 98
  6.4.2 Behavioural Responses ....................................................................................... 100
  6.4.3 Emotional Responses ......................................................................................... 101
  6.4.4 Self and Nurse Observation of Responses ......................................................... 102
  6.4.5 Clown-Child Observations and Interactions ..................................................... 102
  6.4.6 Nurses’ Observations of Children’s Responses .................................................. 103

6.5 Discussion.................................................................................................................. 103
  6.5.1 Impact of Therapeutic Clowns on Children in a Rehabilitation Setting ............. 103
  6.5.2 Interrelation Among Response Modalities ......................................................... 104
  6.5.3 Children with Severe and/or Multiple Disabilities ............................................. 105
  6.5.4 Strengths and Limitations .................................................................................. 106

6.6 Conclusions................................................................................................................ 108
7 **Theme 2 Variation 2: The Social Environment II** ............................................................... 109

A Multivariate Classification Algorithm for Detecting Change in Physiological State......... 109

7.1 Abstract ................................................................................................................................... 110

7.2 Introduction ............................................................................................................................. 110

7.3 Methods ................................................................................................................................... 112

7.3.1 The Multivariate Classification Algorithm ........................................................................ 112

7.3.2 Comparing Physiological Responses Between Interventions ........................................... 119

7.3.3 Application .......................................................................................................................... 121

7.4 Results ..................................................................................................................................... 122

7.5 Discussion ............................................................................................................................... 122

7.5.1 Strengths and Limitations of the Algorithm .............................................................. 123

7.6 Conclusion ............................................................................................................................. 126

7.7 Acknowledgements ............................................................................................................... 126

8 **Theme 2 Variation 3: The Auditory Environment** ............................................................... 127

A Cardiorespiratory Classifier of Voluntary and Involuntary Electrodermal Activity .......... 127

8.1 Abstract ................................................................................................................................... 128

8.2 Background ............................................................................................................................. 128

8.3 Methods ................................................................................................................................... 131

8.3.1 Participants ......................................................................................................................... 131

8.3.2 Instrumentation .................................................................................................................... 131

8.3.3 Protocol ................................................................................................................................ 132

8.3.4 Proposed Cardiorespiratory Classifier ............................................................................. 134

8.4 Results ..................................................................................................................................... 144

8.4.1 Automatic EDR Detection ................................................................................................. 144

8.4.2 Respiratory and Cardiopulmonary Filter Parameters ...................................................... 144

8.4.3 Classification Results ......................................................................................................... 145
8.4.4 Effect of Presence of Background Noise ............................................................ 147
8.5 Discussion ....................................................................................................................... 147
  8.5.1 Classification Assumptions ................................................................................. 148
  8.5.2 Effects of Background Noise and Time .............................................................. 149
  8.5.3 Limitations .......................................................................................................... 149
  8.5.4 Significance of Study .......................................................................................... 150
8.6 Conclusions ..................................................................................................................... 150

9 Coda ....................................................................................................................................... 152
  9.1 Soundprints of the Profoundly Disabled: The Promise of Physiologically-Generated
      Music ............................................................................................................................... 153
  9.2 Research Questions ......................................................................................................... 157
  9.3 Contributions ................................................................................................................... 158
  9.4 Recommendations ........................................................................................................... 160
    9.4.1 Addressing the Challenges of the Target Population ........................................ 160
    9.4.2 Outcome Evaluation ............................................................................................. 160
    9.4.3 Intelligent Algorithms .......................................................................................... 161
    9.4.4 Triangulation of Different Sources of Data ........................................................ 161
  9.5 Directions for Future Research ....................................................................................... 162
    9.5.1 Creating Optimal Environments for Profoundly Disabled Children ............... 162
    9.5.2 Physiological Classification of Individuals .......................................................... 162
    9.5.3 Emotion Recognition ............................................................................................ 163
    9.5.4 Technology and Self ........................................................................................... 163
  9.6 Closing Remarks ............................................................................................................. 164
References ................................................................................................................................... 165
List of Tables

Table 2-1 Overview of Autonomic Signals ................................................................. 18
Table 3-1 EDA features affected by the three exercises .............................................. 43
Table 5-1 Effective widths ($W_e$) presented to the participant. ................................. 78
Table 5-2 Results of the ISO 9241-9 system assessment. ........................................... 80
Table 5-3 COPM results. ............................................................................................. 80
Table 5-4 Frequency and type of computer use over a 1-week period. ......................... 81
Table 6-1 Overview of study design ............................................................................ 96
Table 6-2 Results of the regression analyses of the ANS data. ................................. 100
Table 6-3 Results of the logistic regression analysis of behavioral responses. .......... 101
Table 6-4 Results of a visual inspection of change in emotional response pre to post intervention. ................................................................. 102
Table 7-1 Intensity of Reaction, $I$ ................................................................................ 122
Table 7-2 Pattern of Response, $P$ ................................................................................ 123
Table 8-1 Summary of Experimental Trials ............................................................... 133
Table 8-2 Auditory startle sound characteristics ......................................................... 134
Table 8-3 Individual cardiorespiratory classifier parameters .................................. 144
Table 8-4 Cardiorespiratory filter classification results ............................................. 145
Table 8-5 Accuracy of classifying EDRs generated with and without background noise .... 147
List of Figures

Figure 1-1: Jahiel and Scherer’s framework for person-environment interaction in disability (Jahiel & Scherer, 2009). Reprinted with permission from Taylor and Francis. 3

Figure 2-1 Potential access pathways for the translation of functional intent into the control of assistive technologies (AAC = augmentative and alternative communication; ECS = environmental control system). 12

Figure 2-2 The layout of the present review. Numbers indicate the corresponding sections of the paper. 14

Figure 2-3 The categories of potential EDA recording techniques. The most popular measurements technique in the literature is highlighted. 16

Figure 2-4 A potential method of accounting for metabolic noise in peripheral autonomic signals. Large amplitude respirations and cardiac accelerations are indicative of electrodermal reactions (EDRs) generated from external stimuli – these can be used as part of a filter to discriminate voluntary from involuntary changes in an individual’s ANS. 29

Figure 3-1 Examples of saw-tooth patterns in EDA features due to mental exercises. Participant 2 was able to exert bi-direction control over EDR multiplicity and EDA mean through mental arithmetic while participant 3 was able to control EDA mean and range through mental music. 37

Figure 3-2 Typical raw EDA signals from a resting trial (top) and an active trial (bottom). 38

Figure 3-3 a) A handcrafted algorithm for classifying 10 s of EDA data. Times $t_1$ and $t_2$ were initialized to 10 and 11 s, respectively. EDA values 0.1 s apart added a pre-defined weight to the evidence of either a resting or active state. b) The evidence is evaluated at $t = 20$ s. The observed EDA signal is classified as the state with the stronger evidence. 39

Figure 3-4 (a) Generation of the centroid of the histogram of EDA first differences for an EDA signal of length $N$. (b) Probabilistic classification algorithm. 41
Figure 3-5  The maximum likelihood gamma fit of the centroids of EDA first differences generated from 20 resting trials (solid line) and 20 active trials (dashed line) for participant 3.. 42

Figure 3-6  Accuracy of the two classification algorithms for an 80-20 split cross-validation.... 43

Figure 4-1  The distribution of features three physiological signals collected from an individual with profound disabilities at rest. Points in blue represent signals collected on day 1, points in red represent signals collected on day 2. The intra-subject variability in the distribution of the features over these two days is clearly illustrated................................................................. 54

Figure 4-2  Electrodermal activity (EDA) patterns of a child with profound disabilities as he is presented with affective stimuli, as determined by his primary caregiver. This figure illustrates EDA patterns: a) at rest; b) when presented with a favourite toy; c) when presented with a picture of family and; d) when presented with medical equipment................................................................. 56

Figure 4-3  The total number of electrodermal reactions (EDRs) generated in training sessions designed to develop contingency awareness between a profoundly disabled child’s electrodermal activity and his environment. No differences are observed between the total number of EDRs during baseline (blue) and during intervention (red) trials in any of the three sessions. ............ 59

Figure 5-1  The final tongue-switch access site. Using her tongue, Kate could lift the switch to generate a left-mouse click, and depress the switch to activate her call bell......................... 72

Figure 5-2  Layout of the participant’s bedroom. The components of the access solution are shaded – the CPU was under the table beside her closet, and the computer display appeared on the television on the mobile table by her bed. ................................................................. 76

Figure 5-3 An example of the targets created based on the ISO 9241, Part 9 Standard to test system performance. The individual was asked to target the shaded circle. ....................... 77

Figure 6-1 Illustration of the experimental setup for physiological signal data collection. ....... 97

Figure 7-1 Raw physiological signals collected over a 5 minute baseline period, followed by a 10 minute intervention period................................................................. 113
Figure 7-2  Features extracted from the raw physiological signals presented in Figure 1. Features are represented as $f(*)$, where * denotes the source of the original physiological signal. 115

Figure 7-3  a) Raw physiological data b) Transformed physiological data c) Outlier with respect to baseline hypersphere. Note: only 3 variables are shown to facilitate visualization. 118

Figure 7-4  a) Examples of intra-subject variability and b) inter-subject variability. 125

Figure 8-1  Typical signals recorded from the EDR sensors. Raw electrodermal activity, respiration and heart rate signals recorded from the ProComp Infiniti hardware. 132

Figure 8-2  Overview of the cardiorespiratory classifier. Electrodermal reactions are identified from the raw EDA signal by the automatic EDR detector. These EDRs are subsequently tested by the respiratory and cardiorespiratory filters to determine whether they were voluntarily or involuntarily generated by the participant. 134

Figure 8-3  Automatic EDR detection algorithm. The mean of the histogram of the derivative of the EDA signal (C) is compared to the threshold (D) to determine whether a one second interval of EDA contains an EDR (Blain, Mihailidis et al., 2008). 135

Figure 8-4  Classification of EDRs within: a) an imagery trial (Block B); b) a quiet resting trial with startles (Block C); and c) an imagery with startles trial (Block D). Solid vertical lines denote the times at which audio startles were presented. 146
List of Appendices

Appendix 1: Theme 2, Variation 2 Interview Transcripts……………………………………186
1 Overture

1.1 Motivation

1.1.1 Children with profound disabilities

The incredible recent advancements in medical technology in Western industrialized countries have led to an increase in the prevalence of individuals who survive previously catastrophic injuries and conditions and require complex continuing care for the rest of their lives (Carnevale, Rehm, Kirk, & McKeever, 2008). Most of these individuals have minimal ability to move and speak, are entirely dependent on ventilators, nutrition systems and multiple caregivers, and have never had a consistent way of interacting with their environment. While these children require an unprecedented level of care, they usually remain cherished members of their families, cared for either in the home, or in an institution (Carnevale et al., 2008). However, their inability to communicate or respond places substantial strain on the family and other caregivers. Caregivers perceive communication to be unidirectional and experience considerable distress and frustration associated with voicelessness and unresponsiveness (Happ, 2001). The children themselves are unable to engage in any form of interaction with their built or social environments. In the absence of embodied and social interactive manifestations of self, the remaining identity of children with profound disabilities is fragile at best.

There is a pressing need to address the realities of the lives of children with profound disabilities. As they are unable to move or speak, it is extraordinarily challenging to recognize the unique embodiment of and to engage in meaningful interpersonal interaction with these silent children; these realities present often insurmountable barriers towards their participation and inclusion in the many aspects of human life, and as a result, they are often not valued as full citizens of the human community. However, these realities often remain ignored. These children often ‘fall between the cracks’, in part because of ambiguous categories and services gaps, but also because an appropriate intervention for these children is not obvious. Medical and clinical interventions that target the personal identity components of individuals with disabilities are rendered ineffective due to the lack of responsiveness of these children, and while some effort is made to change the components of the ‘environment’ of these individuals, the lack of obvious effect of
these changes makes it difficult to empirically justify the cost in energy, time and financial resources to implement these interventions.

Given the absence of an intuitive, practical means of improving the life outcomes of children with profound disabilities, this thesis turns instead to theories of how disability is created and conceptualized, so as to identify potential avenues where an intervention can be targeted to enable society to recognize the unique embodiment of and engage in meaningful interpersonal interactions with these silent children.

1.1.2 Person-environment interaction in disability

Many theories attempt to model how disability is conceptualized and created. The World Health Organization defines disability as “a complex interaction between features of a person's body and features of the environment and society in which he or she lives” ("World Health Organization," 2010). This idea that disability is formed in the interaction between a person and their environment has been formalized by several models, notably the disability creation process (DCP) model of the 1980s (Fougeyrollas, 2006), and the person-environment-occupation (PEO) model in Occupational Therapy (Law et al., 1996). While both of these models address the dual derivation of disability from functional state and from social state, they provide only a ‘snapshot’ in time of the nature of the person-environment interaction. Furthermore, these models focus on the direct interaction between the person and their proximal environment, whereas, especially in the case of children with profound disabilities, interaction with the physical and social environments at the micro-, meso- and macro- levels all come to bear in defining disability and identity. In light of the limitations of these models, this thesis turns instead to a more recent model of person-environment interaction in disability, proposed by Jahiel and Scherer (Jahiel & Scherer, 2009). Their platform for the study of person-environment interaction in disability consists of three major entities: time, the environment, and the body. In this model, the environment is comprised of both the physical and social environments, and body refers to both the physical body and the representations of the body by the self and others in the society. To elucidate these concepts, the model explicitly identifies four elements of the personal component that address how persons define themselves – non-disabled identity, disabled identity, identity projects and imputed identity – and four elements of the environmental component that address both the proximal and reactive environments – the given, reactive, internalized and modified
identity. The interaction between any of these given components at any given time shapes and influences the outcomes of the lives of persons with disabilities. The components of this model and their relationships to each other are illustrated in Figure 1-1.

![Figure 1-1: Jahiel and Scherer’s framework for person-environment interaction in disability (Jahiel & Scherer, 2009). Reprinted with permission from Taylor and Francis.](image)

The focus of this thesis is to identify a means of influencing the outcomes (as defined by Jahiel and Scherer’s framework: e.g., life habits, mood, use of assistive technology, etc.) of the lives of children with profound disabilities. As illustrated in the bottom two boxes of Figure 1-1, these outcomes are directly impacted by the multiple interactions between components of the person and components of the environment over a period of time. For the most part, interventions that aim to influence the outcomes of the lives of children with disabilities attempt to target a specific component of the person (e.g. medical interventions that attempt to correct a functional deficit, life-skills programs), or a specific component of the environment (e.g. social policies that change the social environment, assistive technologies that change the built environment). For reasons outlined in Section 1.1.1, these types of interventions are not obvious for children with profound disabilities. Consequently, this thesis will explore a means of influencing the outcomes of the lives of children with profound disabilities by changing the interaction between the components of the person, and the components of their environment, rather than directly changing the
individual components themselves. The interactional ability of these silent children is extremely limited; considering the absence of voluntary and reliable expressive behaviour and physical signals, this thesis instead explores physiological signals as a means of person-environment interaction for children with profound disabilities.

1.1.3 Physiologically-mediated person-environment interaction

While the somatic nervous system of children in the target population is compromised by various pathologies, the autonomic nervous system which controls internal physiological functions often remains intact. Consequently, this thesis looks towards physiological rather than physical responses to enable interaction between a child with profound disabilities and his or her environment. It is well known that physiological signal changes in the autonomic nervous system are connected to emotional states (Ekman, Levenson, & Friesen, 1983). These connections are subtle and nuanced, and the status of expressive physiology in the emotional response hierarchy is debatable (James, 1992; Schachter, 1964). However, in spite of these challenges, studies have been able to successfully classify emotion according to patterns in physiological signals (Picard, Vyzas, & Healey, 2001). Changes in the physiological signals of children with profound disabilities may therefore provide a potent source of information about their intentions and reactions towards their environment.

This thesis explores the possibility of using physiological signals as a means of enriching the person-environment interaction in individuals with profound disabilities. As illustrated in Jahiel and Scherer’s model of person-environment interaction in disability, changing the interaction between the components of the person and the components of the environment directly influences the outcomes of the lives of the disabled; thus, enriching person-environment interaction has the potential to enable these silent children to reconstruct their identity, increase their sense of personhood by enriching social interactivity, and to change the built and social environments in which they live.
1.2 Research Questions

The concept of physiologically-mediated interaction between children with profound disabilities and their environment will be explored in the framework of two themes: 1) how individuals with profound disabilities can use their physiological signals to interact with their environment; and, 2) how the physiological signals of individuals with profound disabilities can be used to determine the effect of their environmental milieu. These themes will be focused to address the following research questions:

1) What challenges can be and remain to be overcome in teaching individuals with profound disabilities to use their autonomic physiological signals to interact with their environment?

2) What are the outcomes (e.g. effects on life habits, mood) of giving a disabled child the ability to interact with his or her built environment?

3) Do physiological signals of individuals respond differentially to changes in their social and auditory environmental milieux?

Specific objectives as related to each of these research questions are detailed in each Theme and Variation.

1.3 Contributions

The potential contributions of this research are as follows:

1) Critical analysis and consolidation of literature across three disparate fields from the past 50 years pertaining to voluntary control of four autonomic nervous system signals. This literature appraisal rendered both a comprehensive understanding of the physiological systems associated with these four signals and full panoramic of the methods used to bring them under voluntary control. Explicit discussion of the challenges associated with this field was undertaken to guide future research efforts (Blain, Chau, & Mihailidis, 2008).

2) Establishment of empirical evidence demonstrating that a signal of the autonomic nervous system - electrodermal activity - can be voluntarily controlled via mental and
respiratory activities. Two algorithms that can successfully differentiate an individual’s mental state based on patterns of electrodermal activity were developed and presented (Blain, Mihailidis, & Chau, 2008).

3) Identification and substantiation of three key challenges in developing a physiological signal-based access pathway for profoundly disabled children based on a series of case studies with an individual with spastic quadriplegia. Empirical evidence from these case studies were used to consolidate challenges identified in the literature, and practical and concrete suggestions of how these critical issues could be addressed for future rigorous research regarding access pathways for profoundly disabled children were made.

4) Development of a custom-tailored bedside computer access solution using a person-focused approach to match an individual with profound disabilities to a technological solution. A multidimensional assessment toolbox was developed and employed to measure the effect of enriching the interaction between an individual and her environment, and was the first study to employ a multipronged approach to assessing the effect of access on the profoundly disabled (Blain, McKeever, & Chau, 2010).

5) Measurement of the physiological, behavioural and emotional effects of therapeutic clowns on children in a long-term healthcare setting (Blain, Kingsnorth, & McKeever, 2010). This information is essential for establishing rigorous evidence of the positive effects of people in the environment of profoundly disabled children.

6) Construction of a multivariate algorithm to identify and classify changes in four signals of the autonomic nervous system (Blain, Kingsnorth, & Chau, 2010). This algorithm addressed the profound intra- and inter-subject variability of patterns of physiological signals, and was adaptable to analyzing significant change in autonomic state from a variety of physiological signal inputs.

7) Establishment of respiratory sinus arrhythmia as a means of distinguishing voluntarily from involuntarily generated patterns of electrodermal activity, and construction of a classifier that employed this phenomenon to automatically detect and classify electrodermal reactions (Blain, Power, Sejdic, Mihailidis, & Chau, 2010).
8) Formulation of a framework wherein the identity and personhood of children with profound disabilities can be constructed and modulated through physiologically-generated music. This framework outlines the theoretical underpinnings upon which future research in developing identity by enriching person-environment interactions can be developed.

1.4 Layout of Thesis

This thesis layout is inspired by the form of a theme-and-variation composition in music. The two themes upon which physiologically-mediated person-environment interaction is explored are: 1) using an individual’s physiological signals to affect the environment; and 2) using an individual’s physiological signal to assess the effect of the environment. Provided is a compilation of papers that present three variations on each of the two themes, followed by a coda to conclude the composition. The following will detail the layout and content of each theme and its variations. Subsequent to this overture:

**Theme 1 Variation 1** provides a literature appraisal of the areas of biofeedback, polygraphy and mental exercises, which uncovers considerable evidence that peripheral autonomic nervous system signals can be voluntarily controlled and thus have the potential to be used by children with profound disabilities to interact with their environment (Blain, Chau et al., 2008). This variation identifies and discusses three major challenges to working with autonomic nervous system signals, which are addressed in this thesis in Theme 2 Variations 1 to 3.

**Theme 1 Variation 2** presents empirical evidence that a peripheral autonomic nervous system signal – electrodermal activity – can be voluntarily controlled through breathing, music imagery and mental arithmetic by able-bodied adults. This variation describes two algorithms that distinguish between periods of mental activity and rest from electrodermal activity patterns, and illustrates that physiological signals can be used to interact with the environment (Blain, Mihailidis et al., 2008).

**Theme 1 Variation 3** explores the challenges associated with profoundly disabled children using their physiological signals to interact with the environment. Examples from a series of case studies with an individual with spastic quadriplegia are used to consolidate three major issues
identified in the literature, and practical and concrete suggestions are made to inform the direction of future research in this area.

**Theme 2 Variation 1** describes the development and implementation of a bedside computer access solution for an individual with severe and multiple disabilities. A multidimensional assessment strategy is presented and used to illustrate the effect of the built environment on the individual’s life outcomes and habits (Blain, McKeever et al., 2010).

**Theme 2 Variation 2** is divided into two movements. The first empirically evaluates the behavioural, emotional and particularly physiological effects of therapeutic clowns on children with profound disabilities, demonstrating that physiological signals can be used to assess the effect of the social environment on these individuals (Blain, Kingsnorth, & McKeever, 2010). The second presents a multivariate classification algorithm for detecting changes in physiological state, explicitly accounting for the profound intra- and inter-subject variability identified as a challenge in Theme 1 Variation 1 (Blain, Kingsnorth, & Chau, 2010).

**Theme 2 Variation 3** explores the use of cardiorespiratory patterns to identify the effects of the auditory environment on physiological signals. An algorithm that uses respiratory sinus arrhythmia to distinguish between voluntarily and involuntarily generated electrodermal reactions is presented, and the results address the challenge of metabolic noise identified in Theme 1 Variation 1 (Blain, Power et al., 2010).

**The Coda** explores a conceptual framework to enrich the interaction between a profoundly disabled child and his/her environment through physiologically-generated music. The concept of using physiological signals to facilitate person-environment interaction is reiterated, and implications of this interaction on the identity and personhood of the profoundly disabled are discussed.

The reader is advised that section 9.3 presents repeated content.
Theme 1

In Theme 1, this thesis explores how individuals with profound disabilities can use their physiological signals to interact with their environment. To interact with the environment, a person requires a connection - a channel - through which they can make themselves understood to other individuals and through which they can affect change in their built environment. For most individuals, this connection is provided by means of speech and voluntarily controlled movements, but these modalities of interaction are inaccessible to children with profound disabilities. However, these children retain their ability to *sense* the environment, and thus, it is hypothesized that they should have the ability to engage in meaningful environmental interaction, should a channel be provided for them. This theme addresses the first research question of this thesis: What challenges can be and remain to be overcome in teaching individuals with profound disabilities to use their autonomic physiological signals to interact with their environment? The answer to this question, and the potential for physiological signals to be a viable connection that will enable a profoundly disabled child to interact his or her environment is explored, discussed and challenged in the ensuing three variations.
2 Theme 1 Variation 1

Peripheral Autonomic Signals as Access Pathways for Individuals with Severe Disabilities: A Literature Appraisal

This variation provides a literature appraisal of the past 50 years gathering evidence to support the use of physiological signals from the peripheral autonomic nervous system as an access pathway (i.e. a channel to interact with the environment) for people with profound disabilities. An overview of the physiological basis of four autonomic nervous system signals – electrodermal activity, skin temperature, heart rate and respiration rate – is provided, and evidence is gathered from the fields of biofeedback, polygraphy and mental exercises to demonstrate that these four signals can be brought under voluntary control. This variation establishes the conceptual groundwork for the idea of individuals with profound disabilities using physiological signals as a means of interacting with their environment. It also addresses three major challenges associated with this means of interaction, which will be explored and address in Theme 2.

2.1 Abstract

Many individuals with severe and multiple disabilities do not have an access pathway that enables them to interface with their environment because they are not afforded a binary switch that they can reliably control. While recent research has focused on the self-regulation of central signals of the autonomic nervous system (ANS) to create brain-computer interfaces (BCIs) for these individuals, there has been less focus on the peripheral signals of the ANS as an access pathway. An appraisal of the literature in the areas of biofeedback, polygraphy and mental exercises uncovered considerable evidence that peripheral ANS signals can be voluntarily controlled and thus have the potential to be used as an access pathway by the target population. However, the issues of speed, metabolic noise and pathological change must be addressed before peripheral ANS signals can be used as either a complementary or alternative access pathway to existing brain-computer interfaces.

2.2 Introduction

2.2.1 Current Access Pathways to Assistive Technologies

Able-bodied individuals who wish to express a functional intent conventionally use the modalities of speech or gestures as their preferred access pathway to interact with their environment. However, for individuals with severe motor impairments due for example to cerebral palsy, amyotrophic lateral sclerosis (ALS), brainstem stroke or spinal cord injury (herein referred to as the target population), these conventional access pathways are often not under voluntary control (Fager, Beukelman, Karantounis, & Jakobs, 2006). These conditions affect over half a million people worldwide, and have pathologies that cause deterioration of the mechanisms enabling somatic muscle control (Barnett, Mohr, Stein, & Yatsu, 1992). In these situations, assistive technologies such as augmentative and alternative communication (AAC), or environmental control system (ECS) technologies are often used to facilitate the individual’s communication and interaction with his or her environment (Craig, Tran, McIsaac, & Boord, 2005; Fried-Oken et al., 2006; Murphy, 2004).
Figure 2-1 Potential access pathways for the translation of functional intent into the control of assistive technologies (AAC = augmentative and alternative communication; ECS = environmental control system)

Both AAC and ECS assistive technologies can be operated, provided that the user has reliable control of a binary switch. As illustrated by the top arrow in Figure 2-1, this binary switch is traditionally controlled via the muscles of the somatic nervous system. A wide variety of mechanical switches have been developed to exploit various types of controlled motor activities, including for example, head movement (Evans, Drew, & Blenkhorn, 2000), eye blinks (Lancioni, O'Reilly, Singh, Tota, & Antonucci, 2006), eyelid movements (Lancioni et al., 2005), chin movements (Lancioni, Singh et al., 2006), muscle contractions via electromyographic (EMG) switches (Gryfe, Kurtz, Gutmann, & Laiken, 1996) and changes in gaze direction as determined by videooculography (VOG) or electrooculography (EOG) (Bates, Istance, Oosthuizen, & Majoranta, 2007). These aforementioned access pathways, or methods of interfacing with the target assistive technology, are compromised in individuals with severe motor disabilities, either because the pathology of their conditions cause the loss of all voluntary control of their somatic muscles, or because their reliable motor movements are confounded by factors such as involuntary movements and fatigue. In these situations, conventional and commercially available access pathways are ineffective, rendering the individual unable to express functional intent or to interact with his or her environment (Wellings & Unsworth, 1997). That these individual are not afforded a consistent, reliable means of expressing functional intent results in a
When research in the fields such as seizure control and behaviour and cognition demonstrated that individuals could be trained to voluntarily regulate their brain activity (Birbaumer, Beatty, & Legewie, 1977; Kamiya, 1971; Sterman & Friar, 1972), the central nervous system pathway (Figure 2-1, middle arrow) was pursued as an alternative to somatic control. To date, a number of brain signal components have demonstrated the ability to be self regulated, including electroencephalographic (ECG) components such as visual alpha rhythms, slow cortical potentials (SCP) (Birbaumer et al., 1999) and sensorimotor rhythms (SMRs) (Pfurtscheller et al., 2003; Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002), neuronal firing as recorded by invasively implanted electrode arrays (Hinterberger et al., 2004; Kennedy, Bakay, Moore, Adams, & Goldwaithe, 2000; Serruya, Hatsopoulos, Paninski, Fellows, & Donoghue, 2002), and signals measured via magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI) (Hinterberger et al., 2004; Weiskopf et al., 2003) and near-infrared spectroscopy (NIRS) (Coyle, Ward, Markham, & McDarby, 2004; Sitaram et al., 2007). Many of these signals have been harnessed to create a brain-controlled access pathway for the individuals of the target population, often referred to as brain-computer interfaces (BCIs) or brain-machine interfaces (BMIs). While central ANS BCI research has progressed to the point where clinical trials are viable (Birbaumer et al., 2000; Neuper, Muller, Kubler, Birbaumer, & Pfurtscheller, 2003; Sellers & Donchin, 2006), it remains yet to be established whether or not the peripheral signals of the ANS have the potential to be a practical access pathway for individuals in the target population (bottom arrow of Figure 2-1). In particular, the operant conditioning and thus, voluntary control of peripheral ANS signals is still debated (Birbaumer, 2006b; Dworkin, 1993; Miller, 1969). In addition to this uncertainty, utilizing peripheral ANS signals as an access pathway present several unique challenges, including a very slow rate of response (e.g. heart rate, 30 s per trial (Williams & Roberts, 1988)), high metabolic noise and high incidence of pathological change in the target population (Kubler, Kotchoubey, Kaiser, Wolpaw, & Birbaumer, 2001). While some peripheral autonomic signals have been investigated as access pathways (Blain, Mihailidis et al., 2008; Moore & Dua, 2004; Tsukahara & Aoki, 2002; Wilhelm, Jordan, & Birbaumer, 2006), the question of learned control of these signals has yet to be answered and these aforementioned challenges remain unaddressed.
This paper surveys the relevant literature on operant control of selected peripheral autonomic signals as laid out in Figure 2-2. We first present an overview of four autonomic signals of interest: electrodermal activity, heart rate, respiration rate and skin temperature. Subsequently, we appraise the evidence relating to voluntary control of these autonomic signals from three bodies of literature, namely, biofeedback, polygraphy and mental exercises. In light of the additional challenges of forging an access pathway from these signals, we conclude with a discussion of the issues of lengthy response time, metabolic noise and pathological signal change, and how these challenges may be addressed in the context of a peripheral ANS access pathway.

Figure 2-2 The layout of the present review. Numbers indicate the corresponding sections of the paper.
2.3 Overview of Autonomic Signals

2.3.1 Electrodermal Activity

Electrodermal activity (EDA), also commonly known as galvanic skin resistance (GSR), reflects sympathetic cholinergic function that induces changes in the skin’s resistance to electrical conduction. It can be spontaneously or reflexively evoked by a variety of internal or externally applied arousal stimuli (Vetrugno, Liguori, Cortelli, & Montagna, 2003), and has been established over decades of research to be one of the most popular and convenient measures of ANS arousal (Boucsein, 1992). In a cross-section of the human skin, each of the components of the 3-layered organ has constant resistive and capacitive properties, with the exception of the sweat glands. Innervated by the sympathetic branch of the autonomic nervous system, the sweat glands fill with an electrolytic fluid upon cholinergic stimulation, thereby changing the skin’s overall electrical conductance. As such, measuring changes in the skin’s resistive properties yields a sensitive measure of the level and extent of an individual’s sympathetic activity (Fowles, Coles, Donchin, & Porges, 1986). Various arousal stimuli induce responses that initiate changes in EDA, including activation of the amygdala as a thermoregulatory response to startling and threatening stimuli (Edelberg, 1973) or in response to emotional or affective processes (Boucsein, 1992); activation of the hippocampus in response to memory recall (Homma, Matsunami, Yan Han, & Deguchi, 2001); activation of the reticular formation and limbic structures as an orienting response to novel stimulus (Venables & Christie, 1980); and activation from the basal ganglia due to an attention orienting reflex (Boucsein, 1992). These stimuli result in an increase in electrodermal activity of more than 0.05 μS within a 10 second interval - a characteristic change known as an electrodermal reaction (EDR) (Boucsein, 1992). These EDRs are superimposed on a slowly-evolving baseline EDA level, whose changes are a result of homeostatic and thermoregulatory processes, and not indicative of ANS activation (Hot, Naveteur, Leconte, & Sequeira, 1999).

EDA measurement is based on the principle of Ohm’s law, $V = IR$, where V, I and R represent respectively, voltage, current and resistance of the system. To measure R, the resistance of the skin, changes in current and/or voltage are recorded and related to changes in skin resistance via Ohm’s law. Resistance is recorded via two electrodes affixed to the surface of a region of skin containing a high density of sweat glands, such as the palms of the hand and the soles of the feet.
Many variations of EDA recording techniques have been established, as summarized in Figure 2-3. The most well-established method of EDA recording – direct current measurement with a constant voltage source, is highlighted.

Figure 2-3 The categories of potential EDA recording techniques. The most popular measurements technique in the literature is highlighted.

2.3.2 Heart Rate

Both sympathetic and parasympathetic branches of the autonomic nervous system project to multiple regions of the heart; their antagonistic effects enable the heart to respond to the rapidly changing metabolic requirements of the body. The dual innervation of the sinoatrial node enables heart rate to respond to arousal stimuli, yet makes it difficult to determine the precise patterns of heart rate change to stimuli of a specific valence, as these changes are highly stimulus dependent. Antagonistic effects are often observed between pairs of opposing stimuli, for example, heart rate undergoes deceleration when an individual’s attention is focused on gathering sensory information from the environment, and accelerates during introspection and other incidences of dampened sensory input (Lacey, Appley, & Trumbull, 1967). Heart rate has also been strongly correlated with emotional state, decelerating in response to disgust, increasing to a greater degree in negative than in positive emotions, and within negative emotions, increasing to a greater degree in response to sadness in comparison to anger (Edelberg, 1973).
Heart rate is commonly measured by logging the time interval between corresponding points of two successive cardiac cycles, as recorded by techniques such as the traditional electrocardiogram (ECG), a blood pressure cuff inflated to a pressure between 40 – 50 mmHg (Elaad & Ben-Shakhar, 1991), and photoplethysmography (Elaad & Ben-Shakhar, 2006).

2.3.3 Respiration Rate and Amplitude

The body’s control of respiratory musculature is unique, as it is regulated by both autonomic and somatic mechanisms. Somatic control dominates during periods of voluntary inspiration and expiration, such as speech and breath holding, and rhythmic autonomic signals control the diaphragm and intercostals muscles at all other times (von Euler, Cherniack, & Widdicombe, 1986). For some individuals with severe motor disabilities, voluntary control of respiration is not possible, and respiration rate is solely regulated by the ANS. Heywood et al. studied the breathing patterns of an individual with locked-in syndrome, and results indicated that chemical inputs, such as the level of CO₂ in the blood, are integrated in the medulla and cause autonomic adjustments in respiration rate and amplitude to maintain a normal end-tidal P<sub>CO₂</sub> of 39 – 40 mmHg (Heywood et al., 1996). As arousal stimuli may cause metabolic changes that vary the level of CO₂ in the blood, respiration rate and amplitude involuntarily increase during stress and decrease during relaxation.

Respiration rate and amplitude information are commonly calculated from basic algorithms applied to the respiratory cycle signals, as recorded via techniques such as a piezoelectric belt positioned around the thoracic area, translating the expansion and contraction of the lung cavity into changes in voltage (Ben-Shakhar & Dolev, 1996), and low-inertia thermistors attached at the entrance of the nostril, using the detected warmer air exhaled during each respiratory cycle to reconstruct the pattern of respiration (Akre & Skatvedt, 2000).

2.3.4 Fingertip Temperature

Fingertip temperature is a combination of long-term baseline changes that are caused by homeostatic thermoregulatory vasodilation and vasoconstriction of blood vessels in the fingers, and transient changes in cutaneous microcirculation. Among these cutaneous vascular structures are arteriovenous anastomoses (AVAs), which are densely innervated by sympathetic nerve fiber (Hales, 1985). Their response to sympathetic stimulation is dependent on the overall body
temperature; in subjects whose finger temperature is above 33 ± 2 °C, sympathetic stimulation induces vasoconstriction, whereas below this temperature, the basic sympathetic vasoconstrictor tone is high and a vasoconstrictor response is not physiologically possible, consequently, the same stimulus will induce a vasodilator response (Elam & Wallin, 1987). Both vasoconstrictor and vasodilator responses occur after a latency period of approximately 15 seconds, and have durations of 20 to 40 seconds in length (Kistler, Mariauzouls, & von Berlepsch, 1998). These microcirculatory responses have been recorded in response to arousal stimuli such as forced arithmetic, deep inspirations, sudden noises, and pain (Kistler et al., 1998; Krogstad, Elam, Karlsson, & Wallin, 1995), and are an established indicator of the state of an individual’s ANS (Elam & Wallin, 1987).

The minute changes in fingertip temperature are measured by attaching a thermistor to the finger to directly measure temperature change (Kistler et al., 1998), or indirectly through infrared thermography (Pollina et al., 2006), which detects the changes in fingertip infrared emissions over time.

A summary of the physiological origins, stimulus mechanisms and measurement techniques for each autonomic signal discussed in this section is presented in Table 2-1.

**Table 2-1 Overview of Autonomic Signals**

<table>
<thead>
<tr>
<th>Autonomic Signal</th>
<th>Physiological Origin</th>
<th>Typical Mechanisms of Modulation</th>
<th>Measurement Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrodermal Activity</td>
<td>Sympathetic innervation of sweat glands</td>
<td>- Emotional thoughts</td>
<td>- Ag/AgCl electrodes on fingers or sole of foot</td>
</tr>
<tr>
<td>Heart Rate</td>
<td>Sympathetic and parasympathetic innervation of the sino–atrial node</td>
<td>- Internal vs. external attention focus</td>
<td>- ECG</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Emotional state</td>
<td>- Blood pressure cuff</td>
</tr>
<tr>
<td>Respiration Rate</td>
<td>Sympathetic innervation of the diaphragm and intercostal muscles</td>
<td>- Metabolic change</td>
<td>- Plethysmograph</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Emotional state</td>
<td></td>
</tr>
<tr>
<td>Skin Temperature</td>
<td>Sympathetic innervation of the arteriovenous anastomoses</td>
<td>- Emotional state</td>
<td>- Thermistor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Forced arithmetic</td>
<td>- Infrared thermography</td>
</tr>
</tbody>
</table>
2.4 Operant Control of Peripheral Autonomic Functions

Each of the four autonomic physiological signals discussed in Section 2.3 demonstrates a specific, reproducible response to sympathetic stimuli. We now proceed to appraise the literature wherein an individual intentionally and intrinsically generates these arousal stimuli, bringing these autonomic responses under conscious control. Preliminary reviews of the literature identified three areas wherein a number of techniques are used to regulate both individual and combinations of autonomic signals: biofeedback, polygraphy and mental exercises. A subsequent, extensive literature review was conducted in Ovid Medline, Scholars Portal and PubMed, combining the key word *autonomic nervous system* with the keywords *biofeedback* and *polygraphy* OR *lie detection* in separate searches. The literature review for mental exercises was subdivided into three searches: *autonomic nervous system* AND (1) *mental arithmetic*, (2) *meditation*, and (3) *motor imagery*. The search was limited to English communications dating onwards of 1960 and returned 416 references. Subsequently, articles were included if they examined the effect of biofeedback, polygraphy or mental exercise on the autonomic nervous system using either: a) a control group that did not undertake the activities used to generated ANS changes; or b) a pre-post study design, where the ANS signals of an individual were measured prior to and following the intervention. According to these criteria, 31 articles were retained and included in the appraisal. The evidence gathered from this body of literature pertaining to the conscious control of peripheral ANS signals is presented in the following sections.

2.4.1 Biofeedback

Early experiments conducted by Miller, Kimmel and Engel demonstrated operant conditioning of several autonomic signals, and gave rise to the field of biofeedback (Bleecker & Engel, 1973; Miller, 1969; Nikooman, Engel, Vanasin, & Schuster, 1973). In biofeedback, physiological monitoring devices are used to provide individuals with information on the state of one or more of their physiological signals, and individuals are trained to use this feedback to learn to voluntarily regulate these signals. While many instances involving biofeedback training did not withstand clinical trial and rigorous scientific testing, there nevertheless remains a relatively small, but scientifically rigorous body of work that clearly demonstrates that control over an autonomic signal can be attained if an individual receives feedback about the state of a signal as
it changes over time (Birbaumer & Flor, 1999). The physiological signals that are predominantly used as feedback can be classified into three general groups: (1) electromyography (EMG); (2) temperature; and (3) cardiovascular.

### 2.4.1.1 Electromyographic Biofeedback

Electromyographic signals are generated from the electric activity regulating muscle contractions. Studies have demonstrated that while individuals with late-stage amyotrophic lateral sclerosis and motor neurone disease are unable to generate overt physical movement, they remain able to generate sufficient myoelectric activity to be detected by commercial EMG sensors (Gryfe et al., 1996). In EMG biofeedback, displaying the EMG signal enables an individual to learn to regulate this activity, and correspondingly, to regulate muscle tension. A number of pathological states result from either insufficient or excess tension in both somatically and autonomically innervated muscles; EMG biofeedback treatments have been successfully used to teach the individual to consciously regulate these pathological muscles. Its power as a technique to teach individuals to consciously regulate involuntary muscle activity has been illustrated through well-controlled studies. Flor and Birbaumer (Flor & Birbaumer, 1993) randomly assigned 57 patients with chronic back pain and 21 patients with temporomandibular pain to EMG biofeedback, cognitive-behavioural therapy or conservative medicine treatment groups. The biofeedback group received EMG biofeedback from the site of the pain in the form of an auditory tone that stopped when they had succeeding in relaxing the site muscles to a pre-defined threshold. While all three groups improved post-treatment, the biofeedback group demonstrated the most substantial reduction in pain severity. Other studies have also illustrated the ability for individuals to gain mental control over involuntary physiological functions by using EMG biofeedback to develop control over the muscles responsible for voiding disorders. Engel’s treatment of incontinence fed back information on rectal distension to patients, training them to learn external sphincter control within four treatment session (Engel, 1981). Khen-Dunlop et al. used similar EMG biofeedback techniques to treat bladder over-activity. In a pre-post study design, 60 children with voiding disorders received visual biofeedback of their perineal muscles, training over 10 weekly sessions to learn to voluntarily control the tension of the muscle. Six months after the last session, 96% of the children with diurnal incontinence and 83% of the children with nocturnal incontinence were cured or experienced a reduction to at least
half of their previous number of wet episodes per week (Khen-Dunlop, Van Egroo, Bouteiller, Biserte, & Besson, 2006).

2.4.1.2 Temperature Biofeedback

Temperature biofeedback has most often been investigated as a treatment for Raynaud’s phenomena, a painful manifestation of digital artery vasospasm that is typically provoked by cold exposure (Middaugh et al., 2001). These biofeedback studies can be categorized into those conducted with able-bodied individuals, and those conducted with individuals with Raynaud’s phenomena. Able-bodied studies have rigorously demonstrated that providing feedback of fingertip temperature enables individuals to learn to voluntarily increase digital blood flow, which reliably increases their skin temperature. Furthermore, once this behaviour has been learned, the response can be reliably generated without feedback, and in different temperature environments (Freedman & Ianni, 1983; Grabert, Bregman, & McAllister, 1980; Keefe & Gardner, 1979). Studies with individuals with Raynaud’s phenomena also provide evidence that fingertip temperature can be statistically significantly changed at will after temperature biofeedback training, and that once learned, temperature control can be generated without feedback, generalized to locations outside the laboratory, and retained over time (Middaugh et al., 2001). While the results of a recent large (n = 313) multi-center trial demonstrated that temperature biofeedback was inferior to sustained-release nifedipine for treating primary Raynaud’s phenomena, these results simply call into question the clinical significance of biofeedback training as a treatment for this condition, and does not diminish the statistical significance of the results that demonstrate the ability for a physiological function to be voluntarily controlled (Middaugh et al., 2001).

2.4.1.3 Cardiovascular Biofeedback

Within biofeedback research, cardiovascular biofeedback has generated substantial interest as a potential non-invasive treatment of serious cardiovascular diseases. Kristt and Engel (Kristt & Engel, 1975) demonstrated that blood pressure could be brought under voluntary control in the laboratory and surrounding environments using operant conditioning techniques. Five patients with high blood pressure of unknown origin were trained to both raise and lower their blood pressure by monitoring a display of lights that corresponded to their current blood pressure level and the direction of the change that was required. Four of the five subjects were able to evoke
statistically significant changes in their blood pressure in the required direction after approximately 50 sessions. Using identical training techniques, Bleecker and Engel (Bleecker & Engel, 1973) were also able to demonstrate that able-bodied men and subjects with atrial fibrillation were able to learn to slow, speed, or cyclically slow and speed their heart rate.

In the three decades since Engel’s initial studies, studies in the field of cardiovascular biofeedback have mainly focused on whether this technique is effective in the treatment of cardiovascular diseases such as hypertension. The current consensus of medical opinion does not favour the routine application of relaxation and biofeedback to treat hypertension (Kranitz & Lehrer, 2004). Nevertheless, studies have demonstrated that consistent antihypertensive effects have been achieved by biofeedback, especially when the therapy includes a respiratory retraining and a slow breathing component. Aivazyan et al. demonstrated that subjects trained with a combination of relaxation strategies such as autogenic training, biofeedback, and breathing were able to significantly decrease both their systolic and diastolic blood pressure and vascular resistance in comparison to a control group that was simply instructed to relax (Aivazyan, Zaitsev, & Yurenev, 1988). Similarly, in a controlled trial, Patel and North compared a group of subjects who were taught structured relaxation involving yoga and biofeedback to a group that practiced uninstructed relaxation and found significantly greater decreases in blood pressure in the treatment group (Patel, 1973). A recent meta-analytic review of all biofeedback methods of treating high blood pressure found an average decline of 6.7/4.8 mmHg for systolic and diastolic blood pressure respectively, a significantly greater reduction in comparison to inactive control treatments (Yucha et al., 2001). As in the situation of temperature biofeedback treatment of Raynaud’s phenomena, there is ongoing debate on the clinical significance of the results achieved by cardiovascular biofeedback (Birbaumer & Flor, 1999; Kranitz & Lehrer, 2004; Linden, 2006; Tsai, Chang, Chang, Lee, & Wang, 2007).

All three of the aforementioned types of biofeedback have been effective in treating migraine. In a recent meta-analysis by Nestoriuc and Martin (Nestoriuc & Martin, 2007), a review of 55 randomized controlled trials and pre-post trials demonstrated a medium effect size for all three modes of biofeedback intervention for treating migraine. This effect size represents a consistent reduction in symptoms by more than half a standard deviation, which is remarkably high in the area of chronic pain. On average, these effects remained stable for over a year post-treatment, and reduced the frequency and duration of the migraine attacks more than the medication-intake.
2.4.2 Polygraphy

In the field of polygraphy, an individual’s peripheral autonomic signals are monitored as he or she answers a series of questions with the objective of distinguishing truthful from deceptive responses. The Guilty Knowledge Test (GKT) is one such psychophysiological method for the detection of deception and has been extensively studied. In this test, individuals are instructed to respond ‘no’ to a series of multiple-choice questions, each with one option containing details that would be known to the perpetrator of a crime, but not to innocent suspects, and several control alternatives (Lykken, 1981). It is assumed that as the guilty individual deceptively responds ‘no’ to the relevant alternative, his or her autonomic signals will exhibit systematic differences in comparison to those generated as the individual truthfully responds to the control alternative. In a review of 10 GKT laboratory experiments, Ben-Shakhar and Furedy (Ben-Shakhar & Furedy, 1990) showed that across the studies, 83.9% of 248 guilty suspects and 94.2% of 208 innocent suspects were correctly identified, although the validity of the GKT in real life polygraph records is lower (Elaad, 1990). One potential explanation for this discrepancy may be that in the real life situations, guilty suspects practiced countermeasures to avoid detection. These countermeasures are of interest, as they illustrate that subtle physical and mental techniques can invoke deliberate changes in the patterns of an individual’s peripheral ANS response patterns. Physical countermeasures involve practices such as the self-inflection of pain or heavy breathing after a control question to stimulate an ANS response. Mental countermeasures involve practices such as mental relaxation after the presentation of a relevant question to suppress an ANS response, and mental stimulation after the presentation of a control question to deliberately generate an ANS response; the effect of these mental techniques will be the focus of this section.

2.4.2.1 Electrodermal Activity in Polygraph Research

Electrodermal activity is the most popular discriminatory signal for the GKT. Electrodermal reactions (EDRs) are generated in response to recognition events, even when subjects report not consciously attending to the stimulus (Boucsein, 1992; Corteen & Wood, 1977), and as such, would be generated when a guilty subject is presented the details of his or her crime, but would be absent when an innocent subject is presented identical details. Most polygraph studies before 1990 used EDA as the sole dependent variable and were nonetheless able to obtain high accuracy estimates of deception (Davidson, 1968; Giesen & Rollison, 1988). The generation of EDRs in response to recognition has been replicated over a variety of conditions, including motivation to
deceive, perceived accuracy of polygraphy, free or forced choice of deceptive items, mode of response (e.g., verbal or pressing keys) and degree of emotional involvement (Godert, Rill, & Vossel, 2001). Mental countermeasures against this response involve either the suppression of an EDR after a recognition event, or the voluntary generation of an EDR after a control question. In addition, this voluntary control must be exerted within less than ten seconds in order to successfully suppress or realistically generate an EDR. To determine the effectiveness of these countermeasures, Elaad and Ben-Shakhar (Elaad & Ben-Shakhar, 1991) investigated the effect on EDA of invoking relaxing thoughts that dissociate the subject mentally both after the presentation of a relevant question, and continually throughout the GKT. Their results demonstrate that EDRs can be voluntarily repressed via mental relaxation techniques, as the detection of guilty subjects was significantly higher in the group that did not practice countermeasures. Ben-Shakhar and Dolev (Ben-Shakhar & Dolev, 1996) investigated the opposite countermeasure strategy, generating an excitatory ANS response to a control question. In a randomized controlled trial (n = 129), innocent individuals and individuals who committed a mock crime underwent a GKT polygraph test. The individuals who committed the mock-crime were subdivided into 3 groups, each of which was tested under a different condition: group 1 received no countermeasure instruction, groups 2 and 3 were instructed to attempt to deceive the examiner by recalling an emotional situation to generate a response to irrelevant alternatives, and group 3 was given the opportunity to rehearse using this mental countermeasure on a polygraph machine prior to the test. Results confirmed that individuals equipped with the countermeasure strategy were indeed able to voluntarily generate EDRs, thereby significantly lowering detection rates. Furthermore, the amount of prior practice of this countermeasure was not a predictor of an individual’s ability to voluntarily generate EDRs.

2.4.2.2 Respiration in Polygraph Research

The respiration length line (RLL), a combination of both respiration amplitude and respiration cycle time, provides a global score of respiration suppression and is a component of the orienting response (Lynn, 1966). Respiration suppression occurs during the act of deception, and consequently, RLL can be used to accurately differentiate between a guilty and innocent subject (Timm, 1982) and follows EDR amplitude as the second most informative measure in detecting deception (Kircher & Raskin, 1988). In a mock-crime GKT experiment carried out on 270 guilty subjects, Timm (Timm, 1982) reported that RLL was more effective than EDRs in detecting
guilty knowledge. In addition, using a combination of EDA measures and RLL provided higher detection accuracy than either measure did individually.

Intuitively, individuals are more likely to be able to voluntarily control their respiration suppression response in comparison to other physiological signals (e.g., EDA), as respiratory musculature is also innervated by somatic mechanisms. However, Ben-Shakhar and Dolev (Ben-Shakhar & Dolev, 1996) demonstrated that while EDA is affected by mental countermeasures, there are no significant differences in RLL measures between guilty subjects who do and do not practice mental countermeasures. These results indicate that mental activities do not affect respiration patterns; other forms of control are required to generate voluntary changes in this physiological signal.

2.4.3 Mental Exercises

This section further explores other mental techniques used to both suppress and generate consistent changes in an individual’s physiological responses by surveying the literature in the areas of meditation, mental arithmetic and mental imagery.

2.4.3.1 Mental Relaxation and Meditation

Meditation refers to a large variety of mental practices that result in voluntary changes in the state and contents of consciousness (Ballantyne & Deva, 1990). While it has been a constituent of major religions such as Hinduism and Buddhism for centuries, only recently have the physiological effects of this practice been investigated. During Transcendental Meditation (TM), the subject undergoes a state of transcending, an experience described as “taking the mind from the experience of a thought to finer states of the thought” (Maharishi, 1969), and its practice has been linked in basic and clinical research to decreasing anxiety, hypertension, artherosclerosis and substance abuse (Travis, 2001). In an investigation of the changes in autonomic patterns during the state of transcending, autonomic signals were recorded from 30 participants who had been using the TM technique for an average of 5.4 years. Results demonstrated a statistically significant difference in EDA and respiratory patterns during periods of transcending compared to other states of consciousness. Similar results have been achieved in individuals without formal meditation training. Kaushik et al. studied the ANS patterns of 100 patients with essential hypertension during baseline states and states of mental relaxation. Subjects were
asked to lie in a comfortable position and undergo complete mental relaxation by thinking of some pleasant thought for 10 minutes. By practicing these mental relaxation techniques, subjects experienced a significant drop in systolic blood pressure and respiration rate, and a significant increase in fingertip temperature. The investigators concluded that mental relaxation was an effective technique to reduce blood pressure in hypertensive patients, and could also induce significant changes in an individual’s respiration patterns and peripheral skin temperature (Kaushik, Kaushik, Mahajan, & Rajesh, 2006).

2.4.3.2 Mental Stimulation

Tasks requiring mental arithmetic are used frequently in research to generate states of mental stress and stimulation (Allen, Blascovich, Tomaka, & Kelsey, 1991; Katz & Epstein, 1991; Tomaka, Blascovich, & Swart, 1994), and the effects of performing mental arithmetic on the components of the ANS are well studied. During silent arithmetic, individuals experience a significant increase in heart rate, electrodermal activity, the pre-ejection period of the cardiac cycle, cardiac output, and respiration rate, accompanied by a significant decrease in the stroke volume of the heart (Kistler et al., 1998; Tomaka et al., 1994). These changes are observed in the recorded signals within 40 seconds of initiating the mental task. Forced arithmetic also causes statistically significant and reproducible vasodilatory responses in cold subjects (Krogstad et al., 1995).

Another commonly used mental stimulation technique is motor imagery - a mental simulation of voluntary motor actions. During this mental exercise, the autonomic system responds in a similar manner to actual exercise, even though muscle movement does not actually occur (Decety, Jeannerod, Germain, & Pastene, 1991). When elite athletes perform motor imagery of their sport, significant increases are observed in skin conductance levels, heart rate and respiration rate, while skin blood flow, skin temperature and respiration amplitude undergo significant decreases (Akre & Skatvedt, 2000; Bolliet, Collet, & Dittmar, 2005; Deschaumes-Molinaro, Dittmar, & Vernet-Maury, 1992). The degree of these responses is proportional to the mental effort exerted by the subject. Through principle component analysis, Deschaumes-Molinaro et al. (Deschaumes-Molinaro et al., 1992) determined that in the specific tasks of motor imagery of firearm and archery shooting, skin conductance, skin blood flow and skin temperature underwent the most significant changes in response to mental imagery. These
studies demonstrate that both mental arithmetic and mental imagery are effective tasks that individuals can use to voluntarily generate changes in the patterns of their peripheral ANS signals.

2.5 Discussion

The amassed literature suggests that peripheral autonomic signals have the ability to be voluntarily controlled through a variety of mental techniques, and thus, have the potential to become an access pathway for individuals with severe and multiple disabilities. However, the clinical viability of these pathways hinges upon the resolution of at least three significant challenges: 1) the speed of peripheral signals in comparison to central signals; 2) the metabolic noise in peripheral pathways; and 3) the incidence of pathological change in individuals of the target population. Each of these challenges is discussed below.

2.5.1 Challenge 1: Slow Rate of Response

To date, the majority of access channels for those who lack the physical ability to interact with their environment have focused on the central autonomic signals from the brain, and the corresponding developments in the area of brain computer interfaces have been plentiful and impressive (Birbaumer, 2006a, 2006b; Kubler et al., 2001; Wolpaw et al., 2002). The enormous advantage of these central signals lies in the fact that their maximum achievable speed is far greater than what can be achieved with the peripheral autonomic signals. While some EEG-based BCIs have achieved transfer rates of up to 27.15 bits/minute (Ming, Xiaorong, Shangkai, & Dingfeng, 2002), autonomic responses can be reliably detected perhaps once every 30 seconds. For individuals with terminal conditions such as amyotrophic lateral sclerosis (ALS), it is conceivable that the speed and accuracy of their access channel are of utmost importance, forgoing all other considerations. However, for individuals with more stable conditions, this is not necessarily the case. Testimonies from individuals who rely on access technologies indicate that the speed of access may not be the all-pervasive top priority, at the expense of all other consideration. In a survey of 17 ALS patients who were extensively informed of the advantages (e.g., greater speed) of a surgically implanted electrode-based BCI over a non-invasive BCI, 16 refused the procedure in favour of the slower and more error-prone non-invasive device, arguing that when one was completely paralyzed, time was not an issue (Birbaumer, 2006a). The
comments of a father of one of the participants in the Cyberlink research, a brain-body interface for individuals with severe TBI, further illustrates this de-emphasis of temporal urgency:

“Even one definite yes or no response to a question from a head-injured son performed just once a week is a joyful event that no person who is not in this situation can appreciate or fully understand. For him, it fully justifies the trouble of setting up the hardware and software.” (Doherty et al., 2002)

It is conceivable that some individuals in the target population and their caregivers may place a greater priority on factors such as the convenience of instrumentation and aesthetics of their access pathway over its maximum achievable speed (Spinney, 2003; Thornett, 1990). While not suited to all individuals in the target population, a peripheral autonomic signal based access pathways may provide an alternative to the faster central autonomic signal based access pathways, enabling the user to choose the technology that best suits his or her personal needs and lifestyle (Scherer, 2002).

2.5.2 Challenge 2: Metabolic Noise

The primary function of the autonomic system is to maintain homeostasis in the body. Consequently, voluntarily generated changes in the signals of this system will be confounded by a significant amount of metabolic noise, as the body responds involuntarily to environmental stimuli. However, this level of noise does not entirely eliminate the possibility of using peripheral autonomic signals as an access pathway – the pathway is still viable provided that an intelligent system can recognize and discriminate between volitional activity and variations due to instinctive reactions and the maintenance of homeostasis. Several methods can be employed for this purpose. One possibility is to extract information from the combination of various physiological signals. For example, deep inspirations function as sympathetic stimuli, and cause an electrodermal reaction (Krishnamurthy, Ahamed, Vengadesh, Balakumar, & Srinivasan, 1996). If electrodermal activity is employed as an access pathway, knowledge of this respiratory-electrodermal interaction can be used to discriminate between voluntarily generated EDRs, and EDRs that are a result of metabolic processes such as deep breathing or coughing. This so called source-separation technique has been successfully employed to improve the classification accuracy of an EDA-based access pathway; filtering respiration patterns from the raw EDA signal improve one subject’s classification accuracy of resting and excited mental
states (Blain, Mihailidis et al., 2008). Further filtering of the electrodermal signal for metabolic noise can be accomplished by examining the cardiac patterns of an individual. Studies in fields such as emotion recognition illustrate that a startle stimulus elicits both an electrodermal reaction and cardiac acceleration (Turpin, Schaefer, & Boucsein, 1999), while activities such as mental arithmetic elicit an electrodermal reaction and cardiac deceleration (Decety et al., 1991). By tracking cardiac acceleration and deceleration patterns, an intelligent system could potentially discriminate between involuntary and voluntarily generated EDRs, eliminating activations that occur as an involuntary response to startling stimuli. Further work must be done to establish the efficacy of this source-separation approach, summarized in Figure 2-4, to isolate self-regulated change from metabolic noise in peripheral autonomic signals specifically for the purpose of access to the environment or communication.

**Figure 2-4** A potential method of accounting for metabolic noise in peripheral autonomic signals. Large amplitude respirations and cardiac accelerations are indicative of electrodermal reactions (EDRs) generated from external stimuli – these can be used as part of a filter to discriminate voluntary from involuntary changes in an individual’s ANS.

2.5.3 Challenge 3: Pathological Change

Physiological signals vary significantly between individuals, and may undergo further changes in the presence of various pathologies. To create a meaningful access pathway, it is crucial to conduct individual baseline recordings to determine which physiological signals are labile, and therefore potentially usefully for decoding an individual’s mental state. For example, individuals with late-stage ALS must be artificially ventilated to survive (Patterson & Grabois, 1986); clearly, respiration patterns yield no meaningful information about the individual. Similarly, individuals with complete spinal cord injury demonstrate no changes in electrodermal activity below the level of injury (Cariga, 2002). An access channel based on physiological signals for
these individuals cannot include this particular signal. Within the identified labile signals, it is likely that the signal characteristics vary from those of the able-bodied population. For example, the defining characteristics of electrodermal reactions – latency and amplitude – are significantly different between individuals with multiple sclerosis (MS) in comparison to a control group of able-bodied participant (Alavian-Ghavanini, Jazayeri-Shooshtari, Setoudenia, & Alavian-Ghavanini, 1999). In a study with 25 individuals with ALS, all exhibited the ability to produce electrodermal reactions in their hand, but the mean EDR latency was prolonged compared to that of the control group (Dettmers, Fatepour, Faust, & Jerusalem, 1994). However, these pathological deviations from the typical response do not necessarily eliminate an access pathway from consideration. As long as the individual is able to produce a significant change away from his or her typical baseline pattern, the pathway may still be useful. For example, regardless of the baseline latency value of the EDR of an individual with ALS or MS, if the individual is able to voluntarily increase or decrease the latency, this information can be used to create an access pathway tailored to his or her unique physiological patterns. Blain et al. (2007) illustrated benefits of using individually-tailored access pathways in a study with six able-bodied individuals. Using algorithms suited to each individual’s physiological patterns to classify EDA, a subject’s mental state could be classified as either resting or active to an accuracy of over 80%, a higher accuracy than has been achieved in other studies with non-specific algorithms to classify electrodermal activity (Blain, Mihailidis et al., 2008).

2.6 Conclusion

The appraised literature in the fields of biofeedback, polygraphy and mental exercises support the notion of conscious regulation of peripheral autonomic signals using mental activities. If the issues of slow response, metabolic noise and pathological change can be addressed, a peripheral autonomic signal-based access pathway may serve as an alternative or complementary source of information to central autonomic signal-based brain-computer interfaces. Further research to explore the potential and limitations of peripheral autonomic access pathways is warranted.
3 Theme 1 Variation 2

Assessing the Potential of Electrodermal Activity as an Alternative Access Pathway

In the preceding variation, evidence from the literature was consolidated and presented that established that peripheral autonomic nervous system signals could be voluntarily controlled. This chapter focuses on one of these physiological signals – electrodermal activity – and empirically tests the hypotheses that: 1) respiratory and mental activities can be used to voluntarily generate changes in the patterns of electrodermal activity; and 2) computer algorithms can be developed to detect these patterns and differentiate between periods of mental activity and mental rest. The confirmation of these two hypotheses in the able-bodied population establishes electrodermal activity as a viable means of interacting with the environment in the absence of movement, providing the foundation upon which this physiological signal is explored for person-environment interaction with a profoundly disabled individual in Theme 1 Variation 3. The results presented in this variation address Research Question 1 of this thesis; voluntary control of electrodermal activity and the detection of this voluntary change in physiological signals by computer algorithms are challenges that can be overcome in teaching individuals to use their autonomic physiological signals to interact with their environment.

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3.1 Abstract

An embedded multiple-case study was conducted with six able-bodied participants to evaluate the potential of electrodermal activity (EDA) as an alternative access pathway to electronic aids to daily living. Electrodermal signals were recorded while participants alternated between rest and three different mental or breathing exercises. In a subsequent experimental session, the exercise exerting the greatest influence on EDA was used to volitionally generate an ‘active’ state. Two classification algorithms, namely, a probabilistic classifier and a handcrafted rule base were developed and tailored to each individual’s physiological patterns to discriminate between participant states. Through cross-validation, participant state was correctly identified to an accuracy exceeding 80% using either classification algorithm. This result demonstrates that consciously controlled EDA could conceivably serve as a binary switch, and encourages further research towards EDA-based alternative access for people who are locked-in.

3.2 Introduction

Over half a million people worldwide are affected by locked-in syndrome, a condition in which individuals are cognitively aware and conscious, but paralyzed and unable to speak (Barnett et al., 1992). Common etiologies leading to this condition include amyotrophic lateral sclerosis (ALS) and brainstem stroke (Kubler et al., 2001). Currently, commercial augmentative and alternative communication devices rely on the user’s voluntary generation of a reproducible, extant physical response, and therefore are not suitable for individuals who are locked-in. Recent research on brain computer interfaces (BCI) suggests the possibility of establishing new communication and control channels for individuals who are locked-in. Invasive BCIs involve implanting electrodes typically in the motor cortex, coupled with automatic decoding of neuronal firing patterns to control devices such as a computer mouse, or a prosthetic hand (Hochberg et al., 2006; Serruya et al., 2002). However, in a survey of 17 ALS patients, who were well informed of the enhanced communication ability of a surgically implanted electrode, most refused the procedure in favour of a slower and error-prone non-invasive device, the argument being that response time was not an issue when one is completely paralyzed (Birbaumer, 2006a). Non-invasive BCIs extract signal features from scalp electroencephalography (EEG) such as visual evoked potentials, slow cortical potentials, the P300 potential and mu-rhythms (Vaughan, Wolpaw, & Donchin, 1996; Wolpaw, McFarland, Neat, & Forneris, 1991). Although the
literature reports initial success with individuals who are locked-in, some outstanding challenges preclude its widespread clinical uptake at the present time. These issues include lengthy training regimens and high error rates (Birbaumer, 2006a), stigma and discomfort of wearing an electrode cap for extended durations, maintaining conductivity of the electrode-scalp interface and the demand for persistent attentiveness to a visual display (Wolpaw et al., 1991). A seldom-considered alternative to BCI is an interface that exploits autonomic signals such as skin conductance.

Skin conductance, or electrodermal activity (EDA) measures the resistive properties of the skin (Bauer, 1998) that change with the reaction of the autonomic nervous system to anticipation and recognition events (Rohrbaugh, Parasuraman, & Johnson, 1990), meditation (Sudheesh & Joseph, 2000), and stimuli such as music (Khalfa, Isabelle, Jean-Pierre, & Manon, 2002) and pain (Arntz & De Jong, 1993). Unconscious changes in EDA also include electrodermal reactions (EDR) in response to affective stimuli and may provide insight into the functional intent of a locked-in patient. On this premise, Tsukahara et al. (2002) developed a pilot device that discerned unconscious skin potential reactions to determine the letter being rehearsed in a participant’s mind with 47% accuracy (Tsukahara & Aoki, 2002). Research on mental countermeasures in polygraphy and biofeedback has demonstrated that EDA can be brought under conscious control with appropriate training (Elaad & Ben-Shakhar, 1991; Schwartz & Beatty, 1977). Using this evidence and a commercial police-grade polygraph system, Moore and Dua trained a participant with ALS using biofeedback to self-regulate his EDA to reproduce a yes or no response with an accuracy of 61.78% (Moore & Dua, 2004). Through the exploration of different mental exercises and the identification of discriminatory EDA signal features, there remains an opportunity to further improve conscious control and automatic classification of EDA.

The current embedded, multiple case study explores the possibility of using mental exercises in a controlled environment to produce voluntary, measurable changes in EDA while taking into account variation in each individual’s physiological patterns and psychological preferences. Specifically, the study aims to:

1. Identify for each participant the most potent method of creating two discernable EDA states;
Create a classification algorithm that accounts for each participant’s unique physiological patterns to distinguish between the two EDA states; and

Investigate for one individual whether the inclusion of a complementary physiological signal (e.g. respiratory patterns) improves the accuracy of EDA state classification.

3.3 Methods

3.3.1 Design

The research was framed as an embedded, multiple-case study (Yin, 2003). Data were collected in two separate sessions: the first session assessed the effect of three different mental and breathing exercises on EDA, and the second investigated the participant’s ability to voluntarily generate 2 distinct EDA states using an individualized exercise chosen from session 1. Following data collection, two algorithms were developed for each individual to determine how accurately the two EDA states could be classified. The presence of circadian rhythms was investigated for all cases, and for one participant who exhibited rhythmic increases in EDA; the effect of physiological filtering using respiratory data on EDA classification accuracy was investigated.

3.3.2 Participants

A convenience sample of six able-bodied participants with a mean age of 26.3 ± 4.5 years (2 female) was recruited. Participants were healthy and instructed not to eat or consume caffeine one hour prior to data collection to mitigate metabolic influences on the autonomic nervous system. Ethical approval for this study was obtained from the University of Toronto and from Bloorview Kids Rehab (Canada).

3.3.3 Measures

Electrodermal activity (EDA) was recorded using a ProComp Infiniti multi-modality encoder from Thought Technology ("Thought Technology Ltd," 2006) and a laptop computer. EDA was recorded from two 10 mm diameter Ag-AgCl electrodes, attached with adhesive collars on the medial phalanges of the index and middle fingers of the participant’s non-dominant hand. A constant voltage (0.5 V) was applied between the two electrodes and EDA was sampled at a
frequency of 256 Hz. The signal was displayed in real-time on the computer screen as visual feedback for the participant and investigator. For the case wherein physiological filtering was attempted, the participant donned a piezoelectric belt positioned around the thoracic area, which translated the stretch due to expansion and contraction of the lung cavity into changes in voltages. These changes were recorded simultaneously with EDA by the ProComp Infiniti system.

3.3.4 Data Collection

3.3.4.1 Session 1

Prior to data collection, participants were familiarized with the following three sets of exercises, each composed of two activities: (1) alternating between a slower-than-normal and a faster-than-normal frequency of breathing; (2) alternating between mental relaxation and mental arithmetic (continuously subtracting 7 from an initial value of 1000); and (3) alternating between mental relaxation and mentally rehearsing a piece of pleasant music chosen by the participant. Participants alternated sequentially between each activity once every minute, repeating each activity three times for a total recording time of six minutes per exercise. Data were stored for future analysis to determine the physiological effects of each exercise.

3.3.4.2 Session 2

Participants were informed of the results of the previous session. In particular, the investigator advised each participant of his or her most successful method of generating a distinct and reliable change in EDA. Participants were then instructed to sequentially produce alternating resting and active states by practicing the recommended mental or breathing exercise. To investigate the presence of circadian rhythms, data were collected on two different days, at different times (e.g. morning, afternoon or evening). The individual generated 10 resting and 10 active states on the first day, and 15 resting and 15 active states on the next day, for a total of 50 sets of signals. Prior to generating each state, each participant was given the opportunity to observe his or her EDA signal for a total of 10 seconds, and was instructed to produce the required state for the subsequent 10 seconds.
3.3.5 Feature Extraction

The raw data collected in session one was used to determine the exercise that produced the most consistent and distinct changes in EDA. From the EDA signal corresponding to each one-minute activity, three features were derived for this purpose, namely, the mean EDA value, the range and the number of EDRs. Baseline EDA signals can naturally increase and decrease by 0.05 μS within as little as 30 seconds. To distinguish transient EDRs from these baseline changes, a 0.05 μS increase in EDA was considered a valid EDR only if it occurred within a timeframe of at most 5 seconds. Each feature was calculated over the full minute of recording. The value of each of these three features was plotted against time for the 6-minute exercise, with one data point for each minute. A saw-tooth plot, as shown in Figure 3-1, indicated that the participant was able to voluntarily increase and decrease that feature of their EDA. For most participants, the 6-minute recording sessions exhibited a dominant increase or decrease in the baseline EDA signal. This trend skewed the data and would have inflated the variance of the means, had they been pooled across similar activities. Consequently, the means of each activity were instead analyzed to determine whether EDA in one state differed significantly from EDA signals in the previous state by comparing successive resting and active states via a student’s t-test (e.g. Resting trial 1 vs. active trial 1, active trial 1 vs. resting trial 2). If each of these EDA states was significantly different (p = 0.05) from the preceding EDA state, the mean was considered a distinguishing feature between states. For the EDR multiplicity and EDA range features, we simply confirmed that the slopes of the lines joining feature values of successive states alternated consistently between positive and negative values. The corresponding mental or breathing exercise was marked as having the potential to control EDA. For data collected in the second session, two different features were extracted, namely, the first difference of the EDA signal and the centroid of the EDA first difference histogram, for purposes of classification. These new features were selected because visual inspection of the EDA signals indicated that the slope of the signal might have more discriminatory potential than the three general features examined in session 1. The computation of these features will be explained below.
Figure 3-1  Examples of saw-tooth patterns in EDA features due to mental exercises. Participant 2 was able to exert bi-direction control over EDR multiplicity and EDA mean through mental arithmetic while participant 3 was able to control EDA mean and range through mental music.

3.3.6 Classifier Design

3.3.6.1 Handcrafted Rule-Base

From the 50 signals collected in session two, a random subset of 40 signals was used to derive a handcrafted rule base for each participant, using the first difference of his or her electrodermal signals. This rule base produced the cumulative evidence, $E_{active}$ and $E_{rest}$, of the participant being in either a relaxed or an excited physiological state. The rule base exploited two observed behaviors: firstly, an individual’s EDA tended to decay over time at rest (Figure 3-2, top), causing the first difference of the signal to be smaller, predominantly negative numbers, and secondly, EDRs were typically present in active states (Figure 3-2, bottom) causing the first
Figure 3-2 Typical raw EDA signals from a resting trial (top) and an active trial (bottom).

difference of the signal to have large positive and negative numbers in comparison to the resting state. While these overall trends were consistent between participants, every individual’s EDA signal characteristics (e.g. EDR amplitude, rise time or recovery time) were unique; consequently, a unique rule base was established for every individual. EDA values were collected with a 1 second time delay at times $t_1$ and $t_2$, where $t_2 = t_1 + 1$. The difference between the EDA values at these times was denoted as $\Delta$. The size of the difference was assigned different weights of evidence, according to the rule base, which consisted of the following two families of if-then rules.

If $\Delta$ is in the interval $(A_{i-1}, A_i)$, then the evidence for active state, $E_{\text{active}}$, increases by $W_{i=a}$.

If $\Delta$ is in the interval $(R_{i-1}, R_i)$, then the evidence for rest state, $E_{\text{rest}}$, increases by $W_{i=r}$.

where $i=1, \ldots, n$ while $A_i$ and $R_i$ were real values that partitioned the range of possible difference values, $\Delta$, into $n$ bins. Hence, there were $2n$ rules in total. In the present experiment, $n$ ranged from 3 to 7. The weights $W_{i=a}$ and $W_{i=r}$ were positive real numbers whose magnitude reflected the level of evidence for the active or rest states, respectively. Both the weights and partition values ($A_i$ and $R_i$) were manually selected to minimize classification error on the training data. The flowchart outlined in Figure 3-3 demonstrates the offline accumulation of evidence from the raw
EDA signal. In accordance with the observations of overall EDA trends, positive $\Delta$ generally contributed to the evidence of an active state while negative $\Delta$ strengthened the evidence of a resting state. Evidence was accumulated every 0.1 s until the end of the 10-second recording. Figure 3b illustrates the evaluation of evidence at $t = 20$ s to classify the observed EDA signal. The signal was classified as the state with the stronger evidence.

**Figure 3-3** a) A handcrafted algorithm for classifying 10 s of EDA data. Times $t_1$ and $t_2$ were initialized to 10 and 11 s, respectively. EDA values 0.1 s apart added a pre-defined weight to the evidence of either a resting or active state. b) The evidence is evaluated at $t = 20$ s. The observed EDA signal is classified as the state with the stronger evidence.
3.3.6.2 Probabilistic Classifier

The second classifier used to analyze the individual’s EDA state was based upon a histogram distribution of the EDA signal differences. Similar to the handcrafted classifier, EDA values were differenced between times \( t_1 \) and \( t_2 \), where \( t_2 = t_1 + 1 \) seconds, the values of which were incremented by 0.1 seconds for the duration of the 10-second signal. Subsequently, a 20-bin histogram of the trial’s cumulative differenced signal was derived yielding a set of bin counts \( \{n_1, n_2, \ldots, n_{20}\} \) and bin centres \( \{x_1, x_2, \ldots, x_{20}\} \). From the bin counts and centres, the first difference histogram centroid was estimated, as depicted in Figure 3-4a. For a given collection of training signals from the resting and active trials, this procedure yielded two sets of centroids. A maximum likelihood gamma fit to each set of data yielded \( F_{\text{active}} \) and \( F_{\text{rest}} \) as the estimated active and rest class distributions, respectively. As an example, the probability densities corresponding to these class distributions for participant 3 are depicted in Figure 3-5.

For classification, a simple Bayes rule was implemented with equal class priors. For each EDA test signal, the centroid of the first difference histogram was computed and the probabilities of resting and active states were estimated from the corresponding class distributions. The probabilities of the centroid, \( C \), arising from active and rest states are compactly written as,

\[
P(C | \text{rest}) = H(C - \mu_{\text{rest}}) - \text{sgn}(C - \mu_{\text{rest}})F_{\text{rest}}(C)
\]

(1)

\[
P(C | \text{active}) = H(C - \mu_{\text{active}}) - \text{sgn}(C - \mu_{\text{active}})F_{\text{active}}(C)
\]

(2)

where \( H(\cdot) \) and \( \text{sgn}(\cdot) \) are the heaviside and sign functions, respectively, and \( \mu_{\text{rest}} \) and \( \mu_{\text{active}} \) are the means of the estimated gamma class distributions, \( F_{\text{rest}} \) and \( F_{\text{active}} \). For example, in equation (1), if \( C \geq \mu_{\text{rest}} \) then \( P(C | \text{rest}) = 1 - F_{\text{rest}}(C) \) and likewise, if \( C < \mu_{\text{rest}} \) then \( P(C | \text{active}) = F_{\text{rest}}(C) \). A maximum \textit{a posteriori} probability decision determined whether the test signal would be classified as a rest or an active trial; this classification was compared against the true state of the participant for the particular trial. The classification procedure is summarized in Figure 3-4b.
Figure 3-4 (a) Generation of the centroid of the histogram of EDA first differences for an EDA signal of length $N$. (b) Probabilistic classification algorithm.
To evaluate each of the above classifiers, an 80-20 split cross-validation was performed on the data from each participant.

3.4 Results

3.4.1 Session 1

Each participant demonstrated at least one exercise that produced a distinct change in an EDA feature between resting and active states. Features that were thus affected by mental exercises are indicated for each participant in Table 3-1. The list of features corresponding to the exercise selected for session 2 is punctuated with an asterisk.
Table 3-1  EDA features affected by the three exercises

<table>
<thead>
<tr>
<th>Participant</th>
<th>Exercise</th>
<th>Breathing</th>
<th>Math</th>
<th>Music</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mean*</td>
<td>Mean, #EDR</td>
<td>Mean, range, #EDR</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Range</td>
<td>Mean, range, #EDR*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Mean, range</td>
<td>Mean, range, #EDR*</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>#EDR*</td>
<td>Mean, range, #EDR*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>#EDR</td>
<td>Range</td>
<td>Range, #EDR*</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Mean, range, #EDR*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The asterisk at the end of a feature list indicates that the corresponding exercise was recommended for the generation of an active state.

3.4.2  Session 2

Results from classifying the data with the handcrafted rule base and the probabilistic classifier are presented in Figure 3-6. On average, participant mental state was classified to an accuracy of $84.7 \pm 11.6\%$ using the handcrafted rule base, and $83 \pm 14\%$ using the probabilistic classifier. Further analysis of the probabilistic classifier demonstrated a positive predictive value of participant’s mental state of $91 \pm 6\%$.

Figure 3-6  Accuracy of the two classification algorithms for an 80-20 split cross-validation.
3.5 Discussion

This study endeavored to evaluate whether or not individualized mental exercises could be used to produce discernible EDA. The results of the investigation demonstrate that this indeed is possible with able-bodied individuals, and encourage further study of EDA as an access point in individuals with severe motor disabilities. Current work with brain computer interfaces suggests that users may need several months of training to develop proficient control over their physiological signals (Neumann & Kubler, 2003). Participants in this current study received no prior training on self-regulation of their electrodermal activity, and were able to generate the correct machine discernable state with over 80% accuracy.

3.5.1 Physiological Basis

The components of the skin have constant electrical properties, with the exception of the sweat glands, which permeate the dermis and are innervated by the sympathetic nervous system (Venables & Christie, 1980). When the autonomic nervous system is stimulated, ion channels in these sweat glands open and the glands fill with sweat, changing the overall electrical conductivity of the skin. Previous studies have demonstrated that mental arithmetic tasks and listening to music provide substantial stimulation to generate an autonomic response (Khalfa et al., 2002; Tomaka et al., 1994), which is confirmed by the changes in electrodermal activity observed in this study. The connection between a single deep breath and electrodermal reactions has also long been established, and research supports the theory of a cortical interaction between respiratory neurons and the central autonomic system (Seto-Poon et al., 2005). This theory would account for the observed changes in electrodermal activity due to the breathing exercises in this study.

3.5.2 Individual Tuning

To reduce the risk of technology abandonment and to maximize user satisfaction, a user-centered approach to assistive technology development is often recommended (M.J. Scherer, 2002). The present access system can be customized to the participant in several ways:

1. Personalized mental exercises. A unique set of mental exercises can be determined for each individual. This is critical to choosing a successful means of EDA control, as the
effect of different cognitive tasks varies from individual-to-individual (Curran & Stokes, 2003).

2. Adaptive classification algorithms. Both classification algorithms described above have free parameters (e.g., feature partitions in the handcrafted rule base and class distribution parameters in the probabilistic classifier) that are customizable to the individual’s EDA patterns during the classifier training stage.

3. Admission of unique physiological signals. Physiological patterns unique to a given individual can be used to enhance classification. Consider for example, participant 6 for whom handcrafted and probabilistic algorithms yielded low classification accuracies (66% and 59%, respectively). Visual inspection of EDA data revealed a repetitive sinusoidal-like pattern of rise and falls, roughly corresponding to the participant’s respiratory patterns. These non-specific EDRs overwhelmed the EDRs produced by voluntary control. During the second session, participant 6 donned a respiratory sensor thoracically to track respiratory patterns. Subtracting the respiratory signal from the EDA data roughly removed the EDRs that were not a result of mental stimulation, and significantly increased the classification accuracy of the handcrafted rule base from $66 \pm 15.6\%$ to $75 \pm 15.6\%$ (student’s t-test, p = 0.05). Other methods of removing the sinusoidal breathing trend, such as wavelet detrending, may also be applied. While visual examination of the EDA patterns of the other participants did not reveal any rhythmic components similar to those of participant 6, these results indicate that for some individuals, exploitation of other physiological signals such as blood pulse volume and respiration rate may enhance the accuracy of classifying the participant state.

3.5.3 Effect of Seasonal and Biological Rhythms

Studies have demonstrated that EDA levels increase linearly throughout the day (Hot et al., 1999), and are affected by season (Venables & Mitchell, 1996). This raises the concern that a classifier trained on EDA signals from one isolated period of time will have difficulty with classification as the signals evolve over time. To capture the potential signal variability due to circadian rhythms, data for this study were collected on three different days and at different times (morning, afternoon, or evening) for each participant. The first session occurred on one day and the second session spanned two different days. Training and testing sets were drawn from the
accumulation of data across the latter two days. The inherent assumption of this method of data collection was that the mental or breathing exercises exerted the same effect on EDA signals at different days and times, irrespective of baseline EDA levels. The approximately equivalent number of classification errors between the two days of testing suggests that transient EDA changes were similar on both days. Additionally, the overall accuracy of over 80% would imply that the exercises had similar effects over all 3 days of data collection. While these results support the assumption that the baseline circadian rhythms do not affect transient EDA behaviour, more extensive data collection is necessary to systematically gauge signal variability due to natural rhythms.

3.5.4 Detection Times

In the present setup, participants were given 10 seconds to calibrate their EDA, and 10 seconds to generate the desired state for a total detection time of 20 seconds. Venables and Christie (Venables & Christie, 1980) recommend a latency window of 1-3 seconds to detect EDRs, and Fowles (Fowles, 1988) suggests an even shorter window of 1-second post stimulus, claiming that changes in EDA can be reliably detected in this timeframe. While a shorter EDA change detection time seems justified, it must be noted that these recommendations have stemmed from consideration of unconscious EDR in response to a stimulus. Detection times for voluntary changes in EDA will likely be user-dependent and several seconds longer taking into account the time required to mount the conscious response. However, EDA response detection time might be reduced by simultaneously monitoring other autonomic physiological signals to corroborate early signs of change. Furthermore, practice, as suggested by biofeedback research, may improve a user’s ability to swiftly generate a desired autonomic state.

Using the handcrafted rule base, an average of 2.6% of the trials in the 80-20 cross-validation resulted in equal probabilities for the resting and active states. In an on-line bedside system, equal probabilities would lead to classifier indecision and consequently necessitate a repeat of the question posed to the user, thus reducing the overall rate of information transfer. In the present experiments, the probabilistic algorithm did not experience any indecisions.
3.5.5 EDA Signal Features

In the current study, EDA mean, range and derivative, and number of EDRs provided simple summary values of the participant’s EDA signals. Other potentially more discriminating features, such as dominant spectral components or detrended signal spread, may be uncovered through further study of EDA signals representing relaxed and stimulated states.

3.5.6 Limitations of Present Study

This study was conducted with healthy individuals in a controlled environment. EDA results of able-bodied participants likely do not reflect performance with the target population. While EDA has been recorded from potential target populations such as people with multiple sclerosis and amyotrophic lateral sclerosis (Alavian-Ghavanini et al., 1999; Miscio & Pisano, 1998), it is likely that these etiologies may result in marked alterations in EDA signals. The proposed classification algorithms may accommodate such individual idiosyncrasies, but further research with the target population must be conducted before conclusions can be drawn about the practical viability of the EDA access channel.

Minimizing external noises and disturbances, which is likely not possible at a participant’s bedside, ideally suppressed contamination from non-specific EDRs in this experiment. Heightened occurrence of non-specific EDRs in unconstrained environments would decrease classification accuracy, necessitating the development of selective EDA filters.

Participants were cued to begin a given exercise to change their physiological state, enabling the investigator to hand-splice events in the offline analysis. To be viable as a bedside system, the user’s voluntary EDA signal changes must be recognized by the classifier without an external cue, potentially via automatic segmentation of the signal.

3.6 Conclusions

This embedded, multiple-case study investigated the possibility of using mental or breathing exercises to generate two machine-discriminable states in a participant’s electrodermal activity. Each of the six able-bodied participants had at least one mental or breathing exercise that produced bi-directional control of an EDA signal feature. Handcrafted and probabilistic classifiers discriminated between excited and resting states with an accuracy of $84.7 \pm 11.6\%$ and
83 ± 14% respectively. These results demonstrate the potential of voluntarily generating distinct EDA signals for the purposes of environmental control. However, future research with individuals who are locked-in will be necessary to ascertain the practical utility of EDA as an alternative access pathway.
4 Theme 1 Variation 3

Challenges of Developing a Physiological Signal-Based Access Pathway for Children with Profound Disabilities

Building upon the evidence presented in the first two variations in this Theme, which illustrated the potential for physiological signals to be voluntarily controlled by individuals for the purposes of environmental interaction, this variation explores the challenges associated with realizing physiological-mediated person-environment interaction for children with profound disabilities. Through a series of case studies with an adolescent born with spastic quadriplegia, this variation highlights three challenges associated with physiologically-mediated interaction between a disabled child and his environment, and proposes practical and concrete suggestions to overcome these challenges in future research with this population. This variation explicitly describes the current limitations of using physiological signals as a medium for disabled individuals to influence and act upon their environment, addressing Research Question 1 of this thesis by elucidating the challenges that remain to be overcome in this endeavour.

Manuscript in preparation for submission to Disability and Rehabilitation.
4.1 Abstract

The growing population of children with profound disabilities who do not have the ability to reliably move or speak has catalyzed many studies investigating various physiological signals as a means of enabling these children to interact with their environment. The majority of this research has been conducted with able-bodied individuals, or with individuals with acquired disabilities. This research cannot be translated to the target population until three challenges of significance to children born with profound disabilities are addressed: the profound intra-subject variability of physiological states; the complete reliance on third-party interpretation of intent, and; learned helplessness. Potential methods of overcoming these challenges are discussed, including the development of algorithms with continually adapting baselines, the need to account for routine, space and context in assessing preference and communicative intent, and the use of techniques such as Intensive Interaction to develop contingency awareness of the environment. Only when these challenges are overcome can the promise of physiologically-mediated interaction between profoundly disabled children and their environment can be realized.

4.2 Introduction

In his book The Boy in the Moon: A Father’s Search for His Disabled Son, Ian Brown writes of the reality of living a son who has complex and profound disabilities - an individual whose life was not possible until recently; “because until 20 years ago, children this medically complex didn’t exist. They didn’t survive. High-tech medicine has created a new strain of human beings who require superhuman care. Society has yet to acknowledge this reality” (Brown, 2009). The incredible recent advancements in medical technology in Western industrialized countries have increased the prevalence of individuals who survive previously catastrophic injuries and conditions, and require lifelong complex continuing care for the rest of their lives (Carnevale et al., 2008). Most of these individuals have minimal ability to move and speak; are entirely dependent on ventilators, nutrition systems and multiple caregivers; and have never had a consistent way of interacting with their environment. As a result, these individuals have minimal opportunity to engage in social interaction, compromising their ability to manifest selfhood and identity (Kitwood, 1997).
Recent research in rehabilitation has investigated methods of enriching the interaction between individuals with profound disabilities and their environment. If individuals have a reliable, voluntary motor movement, a large range of assistive technologies have been developed to harness that movement and translate it into a variety of communication and environmental control functions. For a full review of these technologies, the interested reader is referred to (Tai, Blain, & Chau, 2008). Some individuals with more severe disabilities retain some ability to move, but are unaware of any cause and effect relationships between their movements and changes in their immediate environment. In these cases, considerable effort has been devoted to creating training programs to develop contingency awareness between the residual motion and a response in the environment. In particular, substantial research has been conducted investigating microswitches that allow children with multiple disabilities to access their immediate surroundings and to activate pleasure-evoking stimuli (Lancioni, 2001; Lancioni, O'Reilly et al., 2006; Lancioni et al., 2005; Lancioni, Singh et al., 2006). However, there remain a subpopulation of individuals with disabilities who do not have any form of reliable motor control, rendering them unable to move and/or speak; these individuals are often considered to exist in a vegetative or a minimally conscious state, depending on their perceived level of consciousness (Bosco et al., 2009). Those who retain a high level of consciousness are often diagnosed with “locked-in syndrome” (Laureys et al., 2005). For these individuals, research has moved away from harnessing physical signals and has instead turned toward conscious control of physiological signals to create meaningful person-environment interactions.

Physiological signals of both the central and autonomic nervous system have the potential to be consciously controlled via deliberate manipulation of mental or emotional state; an individual with profound disabilities may be able to learn to control his physiological signals despite an inability to engage in motor movement, and thus, if these changes are captured, learn to interact with his or her environment (Birbaumer, 2006b; Blain, Chau et al., 2008). Substantial research has been conducted, especially in the area of brain-computer interfaces, to develop algorithms and training programs necessary for an individual to use such an interface (Birbaumer, 2006a; Kubler et al., 2001; Wolpaw et al., 2002). However, with a few exceptions i.e., (Birbaumer et al., 2000; Kubler, Neumann, Wilhelm, Hinterberger, & Birbaumer, 2004; Sellers & Donchin, 2006), most of this work has been conducted with able-bodied individuals. Research that has been done with the target population has focused on individuals who have acquired a voiceless,
motionless condition as the result of an event such as brain-stem stroke, or a disease such as amyotrophic lateral sclerosis. The cognitive abilities of these individuals before they acquired a profound disability have been established, and they retain the awareness that they are able to affect change on their environment. To the authors’ knowledge, minimal work has been done establishing physiological signals as a means of environmental interaction with individuals with profound, congenital disabilities. While research with able-bodied individuals and those with less severe disabilities are informative, there remain many issues to establishing physiologically-mediated interaction that are unique to this specific population. This paper will present and describe the challenge of working with this target population, drawing examples from a case study of an individual who we attempted to outfit with a physiological signal-based access pathway.

4.3 Participant

The challenges of developing a physiologically-mediated person-environment interaction pathway for a child with profound disabilities will be illustrated in a series of case studies with a child whom we will refer to as Rudy for the purposes of this manuscript. Rudy was a 15 year old boy born with severe spastic quadriplegia cerebral palsy, global developmental delay and visual impairment secondary to birth asphyxia. His medical history included infantile seizures, ongoing respiratory and swallowing difficulties, gastroesophageal reflux, frequent bouts of bronchiolitis and pneumonia. Rudy was dependent on trained caregivers for all activities of daily living and was fed non-orally via a G-tube. He had marked or fluctuating increased tone throughout his extremities, and reduced or fluctuating tone in his neck and trunk. Rudy’s personalized equipment included bilateral wrist splints and ankle-foot orthoses and a Tilt-in-Space manual wheelchair. Rudy had been involved in speech-language pathology services for the past 9 years. Many augmentative and alternative communication strategies and devices that were attempted in the past; to date, none had been successfully used for environmental control or communication, largely due to issues of fatigue and involuntary movement. Consent was obtained, and approval to conduct the study was granted by the research ethics boards of the pediatric center involved in his care.
4.4 Challenge 1: Intra-subject variability of physiological signals

Since the development of biofeedback techniques in the 1960s, significant efforts have been made to teach individuals voluntary control of peripheral autonomic nervous system signals and to detect change in autonomic state. The detection of significant change is complicated by the complex and dynamic nature of the physiological system. Physiological signals fluctuate with the natural rhythms of the human body (Hot et al., 1999) and with a pattern idiosyncratic to each individual (J. I. Lacey & Lacey, 1958); there is profound inter- and intra-subject variability within each signal. While inter-subject variability can be addressed by the practice of training a pattern-detection algorithm on an individual-to-individual basis, the challenge of addressing intra-subject variability has dissuaded much research in this area.

“Autonomic functions (i.e., heart rate, skin temperature) have also been used as input for computers. Indeed, people with motor disabilities can learn to control these functions to some extent using operant conditioning techniques (R. R. Engel, 1977). However, the very slow rate of responsivity (e.g., heart rate, 30 s per trial; (Williams & Roberts, 1988)) and the high metabolic noise of some autonomic responses, as well as the high incidence of pathological changes in locked-in patients, make autonomic functions useless for precise and reliable communication.” (Kubler et al., 2001)

We illustrate this challenge with a series of recordings of Rudy’s physiological signals. Three peripheral autonomic nervous system signals were recorded for 5-minute intervals: 1) electrodermal activity; 2) fingertip temperature; and 3) respiration rate, while the individual was at rest over multiple days. For each second of data collected, we extracted one feature to represent the state of each physiological signal: 1) the average of the first derivative of electrodermal activity (Blain, Mihailidis et al., 2008); 2) the average of the first derivative of fingertip temperature (Kistler et al., 1998); and 3) the respiration length line (Ben-Shakhar & Dolev, 1996). The distribution of these features is represented in Figure 4-1, and are denoted f(EDA), f(temp) and f(resp), respectively.
Figure 4-1  The distribution of features three physiological signals collected from an individual with profound disabilities at rest. Points in blue represent signals collected on day 1, points in red represent signals collected on day 2. The intra-subject variability in the distribution of the features over these two days is clearly illustrated.

The profound variability in the patterns of the signals recorded between day 1 (blue) and day 2 (red) are clearly illustrated in Figure 4-1. Points that fall outside of the cluster that represented a resting physiological state on day 1 are members of the cluster of points representing a resting physiological state on day 2. In other words, what constitutes a significant change in state that should be captured and harnessed for the purposes of environmental interaction one day may be a part of the individual’s resting state the next day. This profound intra-subject variability constitutes an enormous challenge in using physiological signals to mediate person-environment interaction and must be addressed before technologies that capture meaningful interactions can be accurately developed.
4.5 Challenge 2: Reliance on third-party interpretations of preference

As a result of their compromised physical repertoire, children with profound disabilities communicate mostly in a pre- or protosymbolic way - their communicative tools mainly consist of facial expressions, movements, sounds, body posture or muscle tension. This communication is idiosyncratic and context-bound; consequently, the needs, wishes and preferences of these individuals are difficult to interpret and often misunderstood (Grove, Bunning, Porter, & Olsson, 1999; Hogg, Reeves, Roberts, & Mudford, 2001). Usually, the individual who is most intimate with the profoundly disabled is given the entitlement to interpret their behaviour and to assign communicative intent (Goode, 1990). For individuals with acquired disabilities, this interpretation is informed by knowledge of the individual’s preferences and personality prior to the development of their communication difficulties; however, in individuals with congenital disabilities, caregivers do not have this source of knowledge to draw from. In developing a physiological signal-based access pathway, researchers must rely on the third-party interpretation of caregivers as their gold standard on which to assess communicative intent. However, the reliability and accuracy of this gold standard has been contested in clinical and academic settings. Studies have evaluated the relative effect of using systematically assessed preferred stimuli in comparison to stimuli that staff members believe to be highly preferred (Green, Gardner, & Reid, 1997). The results demonstrated the superiority of using systemic preference assessment over staff opinion, calling into question the reliability of third-party interpretations of the preferences and intent of the profoundly disabled. We further illustrate this challenge by comparing caregiver assessment of a child’s expressions of preference to the child’s physiological reactions to various affective stimuli.

Rudy’s primary caregiver, his mother, was asked to choose 10 affective stimuli - five that she believed evoked a strong positive emotion, and five that she believed evoked a strong negative emotion. These stimuli were presented to Rudy in a random order for duration of one minute, while his electrodermal activity (EDA) was recorded. The resultant EDA patterns are illustrated in Figure 4-2.
Electrodermal activity (EDA) patterns of a child with profound disabilities as he is presented with affective stimuli, as determined by his primary caregiver. This figure illustrates EDA patterns: a) at rest; b) when presented with a favourite toy; c) when presented with a picture of family and; d) when presented with medical equipment.

EDA measures the amount of sweat present in the skin, which is directly linked to the state of the autonomic nervous system. Sympathetic stimulation leads to a sudden increase in the amount of sweat in the skin, which is reflected as a sudden increase in EDA of over $0.05 \, \mu \text{S}$ within 5 seconds, known as an electrodermal reaction (EDR). When an individual is at rest, EDA decreases, and there are very few EDRs. When an individual is stimulated, they experience a high frequency of EDRs within their EDA. As illustrated in Figure 4-2a, when Rudy is at rest, his electrodermal activity displays expected patterns – a decreasing trend, with no EDRs. Figure 4-2b presents his electrodermal activity patterns towards a toy that his mother believed evoked a positive reaction. While the valence (i.e. positive versus negative emotion) of the reaction is not clear, it is evident from the number of EDRs in the signal that Rudy is reacting to the stimuli,
confirming his mother’s claim. Figure 4-2c presents Rudy’s EDA patterns to a picture that his mother claim invoked strong positive reactions in him. The patterns of the signal indicate that Rudy is not reacting to the picture, unlike his reaction presented in Figure 4-2b, calling into question the interpretation of preference of his mother. Figure 4-2d illustrates an ambiguous situation. Rudy is presented with leg splints, which his mother claims invokes strong negative reactions. In Trial 1, Rudy does not react physiologically, whereas in Trial 2, Rudy experiences a significant number of EDRs. These examples illustrate the difficulty of determining a reliable gold-standard for assessing preference in children with profound disabilities; the caregiver’s interpretation is sometimes supported by, sometimes contradicted by evidence of the child’s physiological signals; the most accurate source of knowledge of the child’s affective reactions remains ambiguous.

4.6 Challenge 3: Learned Helplessness

Various aspects of the two aforementioned challenges apply to everyone with a profound disability, regardless of their age. Some challenges, however, are unique to those born with profound disabilities, such as the issue of learned helplessness. Those with acquired disabilities, or progressively degenerative disabilities, have experienced an interaction with their environment where their desires and thoughts have caused an effect. In other words, they have developed contingency awareness between their thoughts and their external environment. It is difficult for those with congenital profound disabilities to develop this contingency awareness (Basil, 1992). Due to a severely limited motor repertoire, their means of communicating intent is highly compromised, and they may never have developed the awareness that they have the ability to affect the environment. This may lead to a condition called learned helplessness, where individuals do not try to affect the environment, even when a means is provided, because they have learned that they do not have the ability to do so.

When a means of interacting with the environment is provided for children with profound disabilities, such as a mechanical switch, responses are often variable and inconsistent. In a recent review of switch use in persons with disabilities, Lancioni et al. reported that 8 of the 23 participants did not show differential rates of switch use across the conditions designed to determine whether the switch use was volitional (Lancioni, O'Reilly, & Basili, 2001). In other words, cause and effect learning was not observed. It is not clear whether this is a result of
learned helplessness, or other factors. The cause of variability of responding is a difficult to
determine. It may be due to limited movement, or constraints on movement enforced by
therapeutic positioning or splinting. Other factors, such as side effects of medication, medical
conditions such as seizures, fatigue, and positional discomfort may also result in behaviour
variability (Saunders et al., 2003). Evidence for contingency awareness is often elusive in
people with profound disabilities, and it is important not to rule out learned helplessness as a
contributing factor to this effect.

This challenge is illustrated over a series of 3 three-week training sessions, as the authors attempt
to train Rudy to develop contingency awareness between his electrodermal activity and his
environment. While unable to conclusively determine preference towards affective stimuli, the
sessions presented in Challenge 2 illustrated that Rudy was electrodermally labile.
Consequently, a software program was built for Rudy which mapped his electrodermal activity
to auditory feedback in the form of a changing organ tone. A change in 0.01 μS in EDA was
linked to the change in one semitone of pitch in the auditory output. Thus, the auditory feedback
rose and fell as a direct consequence of Rudy’s EDA levels. The authors wished to train Rudy to
generate a deliberate electrodermal reaction (EDR) as a means of activating a binary switch and
controlling the environment. Using alternating treatment single subject research study design,
Rudy’s EDA was presented to him in 5-minute sessions. During baseline sessions, EDRs were
not rewarded, and during treatment sessions, EDRs were rewarded with an 8-second auditory or
audiovisual clip of music or a movie that his primary caregiver claimed invoked strong positive
reactions. If Rudy developed contingency awareness of his EDA, we expected to see a
significant increase in the number of EDRs generated during the treatment phase in comparison
to the baseline phase, as Rudy would deliberately generate them for the rewards he understands
will follow. The three sessions were conducted at 2-month intervals, and the results are
presented in Figure 4-3:
Figure 4-3  The total number of electrodermal reactions (EDRs) generated in training sessions designed to develop contingency awareness between a profoundly disabled child's electrodermal activity and his environment. No differences are observed between the total number of EDRs during baseline (blue) and during intervention (red) trials in any of the three sessions.
Rudy did not demonstrate the development of contingency awareness of any of the three sessions. As illustrated in Figure 4-3, the average frequency of EDRs in the intervention was not significantly higher than the average frequency of EDRs in the baseline period. While there are some trials, especially in session 1, where the number of EDRs is almost 5 times high than the average number of EDRs during baseline, they are quickly followed by sessions where Rudy generated no EDRs. It is possible that these sessions with a high EDR frequency were simply a reaction to the reward stimulus, the first of which was triggered by a spontaneous EDR.

Research has demonstrated that electrodermal activity can be trained only after participants develop contingency awareness. No evidence of conditioning has been found in the unaware subject with any measure, neither self-rating, psychophysiological measure, nor behavioural indices (Dawson, 2007). This training paradigm has been successfully used to develop contingency awareness in profoundly disabled children in other studies (Lancioni, O'Reilly et al., 2006; Lancioni et al., 2005) As Rudy has not experienced a cause and effect interaction between his body and the external environment, it is likely that learned helplessness is a significant contributing factor to this unsuccessful training. This is a severe challenge in working with children with congenital, profound disabilities, and must be overcome for the successful development of a physiological signal-based access pathway.

4.7 Discussion

While there is growing interest in developing physiologically-mediated interactions between the profoundly disabled and their environment, research in the area of brain-computer interfaces has predominantly focused on able-bodied individuals. What research has been done with the target population has primarily been performed on individual with acquired or degenerated conditions; individuals with congenital conditions who have no previous experience interacting with their environment have for the most part been ignored. The three challenges illustrated above – the profound intra-subject variability of physiological signals; the absolute reliance on third-party interpretations of intent; and learned helplessness – must be overcome before a physiological signal-based access pathway can be successfully developed for individuals of this population. In this discussion, we make recommendations of how these challenges may be overcome, and provide suggestions for future research directions in this area.
4.7.1 Challenge 1: Continually adapting baseline

Of the three presented challenges, the challenge of addressing the profound intra-subject variability of physiological signals may be the least complicated to overcome. Individuals have no ability to control the resting levels of their physiological signals – these are instead affected by contextual factors such as season, time of day and emotional state (Heywood et al., 1996; Hot et al., 1999; Venables & Mitchell, 1996). The baseline levels of both the able-bodied and the profoundly disabled also change according to factors such as circadian rhythms, level of hydration and eating patterns. In recognition of this phenomenon, it is instructive to develop algorithms that continually adapt their baseline to match the changing resting physiological state of the individual. Fields such as anesthesiology that use physiological monitoring to track the state of an individual have determined that without context-sensitive algorithms, the distinction between normal and abnormal physiological measurements is complex and algorithms that do not address the profound intra-subject variability often have poor accuracy (Dosani et al., 2009). We recommend developing algorithms that are recalibrated to the physiological state of each individual of the target population after events that may have a significant effect on baseline physiological state may have occurred, such as eating a meal, a shift in physical positioning, or sleeping.

4.7.2 Challenge 2: Routine, Space and Context

The challenge of relying on third-party interpretation of communicative intent is most often brought to light when the caregiver most intimate with the profoundly disabled individual claims that the individual expresses preference for or responds to a situation or a stimulus, and that claim is not empirically substantiated. This situation is clearly illustrated with the evidence presented earlier in Figure 4-2. Rudy’s mother’s claim that he reacted strongly to certain stimuli was not substantiated by the patterns of Rudy’s physiological signals upon empirical testing – which source of evidence is to be believed? In answering this question, one must account for situations within which both sources of knowledge are generated. In his epistemological research on the communication between a deaf-blind child and her parents, David Goode remarks upon the surprisingly antithetical claims made about the capabilities of the child by school staff and family members. The two parties had generated diametrically opposite ‘versions’ of the child, which lead to a history of fairly serious conflict – these situations are quite commonplace (Goode, 1990). Professional, objective assessments of a disabled child’s
capabilities are often largely divergent from a parent’s understandings of the child’s capabilities, and parental insistence on the truthfulness of their testimony may lead them to be regarded as “delusional” or “disturbed” (Goode, 1990). Often, intimacy is seen as a barrier to dispassionate scientific knowledge.

According to recent theories of person-environment interaction, disability is constructed in the interaction between the components of an individual’s identity and the components of their environment (Jahiel & Scherer, 2009). Identity, understood as a sense of self, is conjectured as having four components: non-disabled identity, disabled identity, identity project and imputed identity. Those who are profoundly disabled are entirely characterized by their disabled identity. Their imputed identity cannot be modified by their non-disabled identity or identity project. As such the ‘person’ that any given individual who they interact with is familiar with is given their identity through the social organization around them. This perspective challenges the conventional view of communicative competences as attributes of individuals rather than of social systems. Hence, in order to truly evaluate the reliability of third-party interpretations of communication intent, one must hold constant the social context within which communicative skills are actualized, given meaning and measured.

The understandings of the intent and preferences of a profoundly disabled individual often arise from the mutual understanding of the details of a task at hand, in other words, the sharing of a routine. Within the context of a routine, the limited expressions of these individuals have the potential to be transformed into gestures with specific, context-relevant content. Similarly, shared knowledge about spatial arrangements and objects provide context through which to interpret expression and preference. As such, situations where preferences and expressions are assessed by professionals must take into account the routine, space and context of the communication. The frequent misunderstanding of needs and preferences of these individuals often arises from the idiosyncratic and context-bound nature of the communicative behaviour (Grove et al., 1999; Hogg et al., 2001). By presenting Rudy with the affective stimuli that his mother believed would evoke an emotional reaction in the routine and space within which they would normally be encountered: 1) professionals would have the ability to understand the contextual factors informing the caregiver’s understanding of the interaction, and; 2) Rudy would have been more likely to engage in the reactions appropriate to the presented stimuli. In conducting experiments that determine preference and reaction within these situations,
researchers can begin to develop their own meaningful interpretations of a profoundly disabled child’s emotions and reactions and, informed by the interpretation and experience of the individual most intimate to the child, may be able to develop an understanding of the intentional communication of these persons without needing to rely solely on the interpretation of a third-party caregiver.

4.7.3 Challenge 3: Contingency awareness training

The challenge of teaching individuals voluntary control of an autonomic signal is well documented in the literature on EEG-based brain computer interfaces (BCIs). Studies that have examined training issues have illustrated that not everyone, regardless of whether they are healthy controls or neurological patients, acquires the ability to regulate components of their EEG and reach the level of proficiency required to control a BCI (Kubler et al., 2001). It is desirable to develop a means of determining whether individuals will have the ability to eventually develop control of their physiological signals; training patients to control a BCI through voluntary manipulation of their slow cortical potentials (SCPs) has lasted from several months up to years, and was conducted two to three days per week for 3-4 hours (Neumann & Kubler, 2003). This represents a significant loss of time, energy and financial resources if the patient is unable to eventually develop control of their EEG components. Strategies, such as assessing the patient’s performance after 30 initial training sessions, have been employed as a means of screening potential participants and minimizing the frequency of unsuccessful training (Kubler et al., 2004).

Additional strategies must be adopted when working with children who have congenital disabilities, and who must overcome learned helplessness, on top of the existing training challenges, to successfully control their physiological signals. Within Rudy’s biofeedback training paradigm, for example, it is impossible to determine whether the evident lack of development of contingency awareness is a result of an innate inability to voluntarily control his electrodermal activity, or a lack of awareness that there exists any connection between his body and the environment (i.e. learned helplessness). To address this challenge, the authors recommend testing the two components independently: first, by establishing an understanding with the child that their actions affect the environment, and second; by training the child to voluntarily control a physiological signal to affect the environment. Training an individual to
develop operant control of a physiological signal is covered extensively in the BCI literature (Kubler et al., 2004; Neumann & Kubler, 2003); we will therefore only address here an example of a strategy tailored to the first component – the development of awareness of the interactivity between a profoundly disabled child and their environment.

One established method of encouraging and enriching the quality of interaction between a profoundly disabled child and his/her environment is a teaching approach developed in the late 1980s: Intensive Interaction (Nind & Hewett, 1994). This approach aims to promote sociability and communication in individuals with severe and complex learning difficulties and who experience difficulties relating to others. It is characterized by regular, frequent interactions between a profoundly disabled individual and an interaction partner where no task or outcome is the focus; it is only the quality of the interaction itself that matters. Intensive Interaction was developed with the underlying premise that the ability to relate to others and to communicate were the primary learning needs for individuals with severe and complex learning disabilities, and were the priority for quality of life (Hewett & Nind, 1998). Studies that have measured six categories of social behaviour (eye contact; looking at face; smiling; contingent vocalization; joint focus; and ‘engaged social interaction’) have demonstrated significant increases in socially interactive behaviours as a result of the Intensive Interaction program (Kellett, 2005). As an awareness of the ability to interact with their environment develops, these children engage in more and more activities that illustrate a contingency awareness between their actions and the state of their environment.

We propose that strategies such as Intensive Interaction be employed with children with profound disabilities who are being considered as candidates for a physiologically-mediated interaction pathway. It is crucial to develop contingency awareness before operant learning of control of a signal such as electrodermal activity can occur (Dawson, 2007). In training only those individuals who have demonstrated an understanding of the interaction between themselves in their environment, the chances of success in developing voluntary control over physiological signals will have a significantly increased chance of success.
4.8 Conclusion

While significant progress has been made in recent years in developing physiological signal-based access pathways for individuals with severe disabilities, several challenges still exist for the increasing population of children born with profound disabilities. A case study of the physiological signal patterns of a boy born with severe spastic quadriplegia illustrated the challenges of profound intrasubject variability of physiological signals, the reliance on third-party interpretation of intent, and the learned helplessness of the disabled child. These challenges must be overcome before physiological signals can fulfill the potential they have demonstrated in the able-bodied population to be used as a means of increasing the interaction between profoundly disabled children and their environment.
Theme 2

In Theme 2, this thesis explores how the physiological signals of individuals with profound disabilities can be used to determine the effect of the environmental milieu on the individual. There are four components of the environment as outlined in Jahiel and Scherer’s theory of person-environment interaction in disability – the given environment, the reactive environment, the internalized environment and the modified environment. All of these exist in varying proportions within the different types of environments that may impact an individual. This Theme focuses on the effect of three types of environments on children with profound disabilities – the built environment, the social environment and the auditory environment. While substantial research has been conducted on the effect of each of these types of environment on able-bodied individuals, the effects of the different manifestations of these environments on children with profound disabilities are virtually unknown. The first variation on this Theme addresses the second research question of this thesis: what are the outcomes (e.g. effects on life habits, mood) of giving a disabled child the ability to interact with his or her built environment?; the second and third variations on this theme address the final research question of the thesis: Do physiological signals of individuals respond differentially to specific changes in their social and auditory environmental milieux? Together, the three variations on this theme serve to explore physiological signals as a means of assessing the effect of the different environment types on children with profound disabilities.
5  **Theme 2 Variation 1: The Built Environment**

**Bedside Computer Access for an Individual with Severe and Multiple Disabilities: A Case Study**

This variation answers the second research question of the thesis: What are the outcomes (e.g. effects on life habits, mood) of giving a disabled child the ability to interact with his or her built environment? While the target population of physiologically-mediated person-environment interaction research remains individuals who cannot move and speak, it is challenging to assess the full range of the effect of introducing environmental access on this population. Consequently, this variation assesses and evaluates the effect of a change in the built environment on an individual who has the cognitive and physical ability to verbally report the impact of bedside computer access system on her life habits. Tongue movements, as opposed to physiological signals, are used to mediate person-environment interaction, such that the scope and impact of introducing a new means of environmental interaction for an individual with limited interactional ability is clearly explored. The presented results illustrate the breadth and significance of the effects that introducing a new channel for person-environment interaction can have, providing justification for the efforts presented in Theme 1. The results of this variation provide insight into the possible range of effects that environmental interaction can have, and inform future research efforts that endeavour to measure the effects of physiologically-mediated person-environment interaction in the target population. Additionally, a person-focused approach for designing a person-environment interaction system are presented and explored, providing framework and guidelines for future development of a similar, physiologically-mediated system.
5.1 Abstract

**Purpose:** This case study documents the process of designing a custom-tailored bedside computer access solution for a 20-year old individual with quadriplegia and reports the effects of computer access on her participation in life activities. **Method:** We adopted a person-focused approach to match the individual to an access solution. Two months after the access solution’s introduction, we measured its impact using a 2-dimensional Fitt’s Law test and questionnaire from the ISO 9241-9 standards document, typing tests, a usage log and a semi-structured interview. The Canadian Occupational Performance Measure (COPM) was also administered pre- and post-access, focusing on the client’s perceived ability to use the computer. **Results:** After 2 months, the individual was spending an average of 8.4 hours per day on the computer, engaging in electronic communication, recreational and educational activities. She learned single-switch typing with a throughput of 1.03 bits/s and targeting accuracy of 87.5%. The questionnaire revealed that the client was thoroughly satisfied with the interface. These results were interpreted as positive gains in the ICF domains of communication and social interaction. **Conclusions:** By addressing individual goals, abilities and relevant environmental factors, a bedside computer access solution can be developed for individuals in long-term care. The introduction of a computer access solution augmented the participant’s communication, leisure and educational activities, as well as perceived independence.

5.2 Introduction

5.2.1 Computer access for individuals with severe and multiple disabilities

Computers pervade nearly every aspect of life in the 21st century, playing key roles in activities such as communication, information retrieval and education. However, compared to the general population, individuals with severe disabilities are less likely to own a computer and to use the internet (Goodman, Jette, Houlihan, & Williams, 2008). To use a computer, these individuals typically require an access method, whereby the user’s intention, manifested either motorically
or physiologically, is translated into a useful input to the computer. Computer access methods can be categorized by the requisite level of voluntary physical movement (Tai et al., 2008). Access technologies range from mouth sticks, tooth-click devices (T. Simpson, Broughton, Gauthier, & Prochazka, 2008), head pointers, eye-activated mice and forehead/eyebrow twitch switches (Man & Wong, 2007) for those with some voluntary motor control, to electroencephalography, electrocorticography and intracortical recordings, for those with no functional movement. The interested reader is referred to (Tai et al., 2008) for a comprehensive review of these and other access technologies. Generally, as an individual’s level of controlled, voluntary abilities becomes more limited, there are progressively fewer viable computer access options. At present, those who are unable to reliably control at least one physical movement typically cannot engage in computer-based activities because they lack an access pathway.

5.2.2 The benefits of computer access

Computer access can have a significant positive impact on academic, communication and recreational activities (Man & Wong, 2007). When conditions completely prohibit communication, as is the case for individuals with locked-in syndrome (LIS), computer access can have a liberating effect. Computer access can facilitate otherwise impossible tasks, such as initiating dialogue and preparing questions and other messages (Smith & Delargy, 2005). An 11-year cohort study of individuals with LIS reported that access to the computer drastically changed their lives, not only by increasing the amount of communication with family and friends, but also by changing the patterns of communication, giving individuals with LIS some control and independence (Doble, Haig, Anderson, & Katz, 2003). In addition to affecting social interaction and communication, computers give individuals with disabilities the ability to independently access information about their health, providing a readily accessible forum for individuals to further educate themselves about their condition, resulting in a positive impact on their overall health (Goodman et al., 2008). In brief, computer access can have a multifaceted impact on the lives of individuals with severe and multiple disabilities, giving them greater independence (Bache & Derwent, 2008; Wu, Meng, Wang, Wu, & Li, 2002), enhanced quality of life (Craig et al., 2005), improved psychological well-being (B.S. Hoppestad, 2007) and broader employment opportunities (Kruse, Krueger, & Drastal, 1996).
5.2.3 Barriers to computer access

While the benefits of computer access are well-documented, the challenges of finding an access pathway for individuals with severe disabilities can be so overwhelming that efforts frequently cease after a few iterations (B.S. Hoppestad, 2007). These often insurmountable barriers include the need for reliable motor control to operate conventional mechanical input devices (e.g., mechanical switches and adapted keyboards), the health professional’s limited awareness or experience of the diverse collection of available devices (Turpin et al., 2005) and the prohibitive cost of customized solutions (Bache & Derwent, 2008; Man & Wong, 2007). Another major barrier is the lack of a universal and comprehensive computer access assessment (B. S. Hoppestad, 2006). While many different systematic assessments for computer access have been proposed (Fraser, Bryen, & Morano, 1995; Meng et al., 2004; Pushchak & Sasi, 2004; Wu et al., 2002), none have been widely adopted. In many instances, finding a successful access solution for a particular individual remains a trial and error process, due to the ‘lack of a valid predictive model’ to guide device selection (B.S. Hoppestad, 2007).

This case study describes the development of a bedside computer access solution tailored to the needs of a young lady with severe disabilities and within the constraints of the specific hospital environment. Through a mix of qualitative and quantitative data, we demonstrate the effects that bedside computer access can have on enabling participation in life activities.

5.3 Methods

5.3.1 Description of the participant

The participant, who we will refer to as Kate, was a 20-year old female who experienced an incomplete C1-C4 spinal cord injury at birth resulting in incomplete quadriplegia. She received constant mechanical ventilatory support via a tracheotomy. She did not exhibit any cognitive impairment and could speak. At the time of writing, Kate had completed her high school education and had aspirations to enter college. The majority of her time was spent lying supine in her hospital bed with her neck laterally rotated and slightly flexed to the right. She had extensive motor impairment with the exception of minimal voluntary movement in her thumb, which could not be dissociated from involuntary activity of her fingers. Kate had voluntary control of her eye gaze, eyebrows and eyelids with no evidence of ptosis. She resided in a
complex continuing care unit with 24-hour nursing support. Nursing staff assisted her with operating the television and the telephone. She received attendant care at school and on outings from the hospital. Kate was medically fragile and frequently transferred to an acute care hospital.

At the time of writing, Kate had amassed six months of experience with a voice recognition system for environmental control that enabled her to use her telephone, fan, and music player. Voice recognition had been limited to the switching of these selected environmental controls due to Kate’s variable voice quality, largely attributed to her mechanical ventilation. The voice system also required caregivers to initialize software and to position the microphone. Kate had also used a sip-n-puff switch for five years to drive her powered wheelchair. However, the sip-n-puff device had been implicated in multiple oral infections in the past. Kate and her health care providers were eagerly seeking an alternative access modality to complement and potentially replace the voice recognition system. In particular, they hoped that a single switch for computer access could be established. Consent was obtained, and approval to conduct the study was granted by the research ethics boards of the pediatric and adult centers involved in her care.

5.3.2 Finding an access site

The initial challenge of creating a computer access solution involved finding a reliable, voluntary movement to operate a binary switch. Criteria for successful switch design included easy set up and removal by caregivers who may not be technology savvy, and accommodation of the participant’s fixed positioning on the bed.

Initial assessments by an interdisciplinary research team (nurse, occupational therapist, rehabilitation engineer) indicated that mechanical switches (Tash Big Buddy Button, Tash Leaf Switch, and a Touch Switch) on her chin and thumb were impractical access alternatives. Due to limited strength and confounding involuntary finger movements, she was unable to voluntarily activate any of the three switches consistently using her thumb. The chin switch could be more repeatedly triggered but challenges of unobtrusive placement and mounting precluded its usage. Additionally, Kate expressed fatigue and frustration with both the thumb and chin switches.

A novel vibration switch was developed to capture the upward movement of her eyebrows. This custom switch consisted of a dual axis accelerometer strategically mounted in a plastic hair band
to sit above the right eyebrow. A microcontroller was programmed to discern voluntary eyebrow raises from other facial gestures with both positive and negative predictive values exceeding 88% over 214 trials. Unfortunately, Kate reported that it was fatiguing to consistently lift her eyebrows, and requested an alternative access solution.

Finally, a switch was introduced that took advantage of Kate’s voluntary tongue movement. The switch was mounted on a microphone stand that was placed directly behind her bed, on the end of a flexible arm that could be easily adjusted in all three dimensions. This mounting allowed Kate to talk freely without involuntarily activating the switch, while simply requiring a tongue protrusion to lift and depress the switch. After an initial trial period, Kate expressed satisfaction with this access site, as it was comfortable, and did not require undue effort on her part to operate. Subsequently, the switch was adapted such that depressing the switch activated the call bell in her long-term care facility, and lifting the switch completed the circuit in an adapted computer mouse, thereby creating the equivalent of a left-mouse click. The solution is illustrated in Figure 5-1. The mouse was connected to a computer system, and thus, by moving her tongue, Kate was able to reliably and reproducibly generate a mouse click on command.

![Figure 5-1](image)

**Figure 5-1** The final tongue-switch access site. Using her tongue, Kate could lift the switch to generate a left-mouse click, and depress the switch to activate her call bell.
5.3.3 The software solution

There is a high rate of abandonment and non-compliance of assistive technologies. Research focusing on user perspectives has concluded that the primary reason for abandonment is device ineffectiveness in helping individuals attain their personal goals (Phillips & Zhao, 1993). Consequently, before we chose software to interface with the binary switch, we interviewed Kate to determine her goals. Her top three priorities were: 1) to e-mail her friends and family, 2) to use the word processor to read and write school assignments, and 3) to surf the internet.

Many commercially available software systems use single-switch scanning to facilitate the selection of letters from an onscreen keyboard. Kate’s needs were more diverse – her wide range of desired activities, in addition to her desire to independently select and switch between them necessitated the introduction of a full software platform. To this end, QualiWORLD, a comprehensive and fully integrated software platform developed by QualiLife, was introduced. QualiWORLD’s user interface arranges the various applications, and the desktop operations (e.g. opening and closing a program), in a manner that enables the user to easily access all options, while accommodating a variety of inputs, including a single binary switch.

QualiWORLD provides different mouse emulation strategies to navigate and select icons on a computer screen using a single, left-mouse click. Examples of these include XY-mouse, which scans the computer screen in a horizontal, then vertical direction; radial-mouse, which scans the computer screen in a counterclockwise, then radial direction; and auto-scan mouse, which sequentially highlights each icon available to the user. The user is able to navigate all available options by pressing the switch to select the currently highlighted item. These three options were presented to the participant, who immediately discarded the radial mouse on the grounds that it was not intuitive. In the subsequent training phase, both the XY-mouse and the auto-scan mouse were made available to the user so that she could test and evaluate both options.

Finally, QualiWORLD comes with a number of modular applications, each enabling access to a different interface. Possible interfaces include the telephone, the radio, the television and the DVD player. To target the goals of the user, three modules were purchased: QualiWORD, an accessible word processing program; QualiMAIL, which enables sending and receiving e-mails, and QualiSURF, an interface which creates an accessible environment through which the user can surf the internet with any of the adapted mouse options presented above. Each of the above
modules was accompanied by an on-screen keyboard, which the participant accessed through row-column scanning.

5.3.4 The physical setup

In order for an assistive technology to be accepted, many believe that it is vital that the device be compatible, not just with the needs of the individual, but also with the environment in which the device will be utilized (Biegel, 2000). Consequently, great care was taken to clarify the expectations of all stakeholders at the long-term care facility regarding an assistive device intended for daily, long-term use by the participant, and to comply with the constraints introduced by the facility and the immediate space around Kate’s bed. The most pertinent constraints are discussed below.

Since Kate was fully dependent on her caregivers for all of her physical needs, unobstructed access to her bedside was required at all hours of the day and night; it was essential that no part of the computer access solution restrict freedom of caregiver movement around her bed, or impede access to any medical equipment located on the walls. This physical space included that which was necessary to bring her power wheelchair beside her bed, and the ceiling space necessary to operate the lift that transferred the participant from her bed to her chair.

Additionally, the process of setting up the tongue switch could not be onerous or require precise positioning, as the staff had limited time and were responsible for many patients. In the case of an emergency, it was necessary that Kate’s bed be made mobile at a moment’s notice; no part of the access solution could be secured or attached to the bed in any manner, and the pathway to the door had to remain barrier free. Finally, Kate might be transferred to another room as the needs and available spaces of the long-term care facility evolved; thus, no part of the solution could be mounted on the walls or ceilings of the room. The computer screen had to be mounted in a position where Kate could easily read text from a supine position, and wires had to be secured in a manner that they did not present a safety hazard to the other occupants and/or visitors of the room.

Several solutions were attempted to address these constraints. The first was to mount the entire computer access system on a Mobile WorkStand by Ergotron. Using this system, the LCD monitor was placed on the end of an articulated arm that could be adjusted so that the contents of the screen were within Kate’s field of view. The entire system was mounted on wheels, and
therefore easily moved around the bedroom according to the current needs of the individuals in the room. However, over the course of several months, many problems became apparent. In constantly needing to move the system to and from the bedside, the tower containing the central processing unit was knocked out of its bracket on two occasions, damaging the hard drive and necessitating the purchase of a new computer. The height of the WorkStand was level with the ventilator system mounted on Kate’s wall, and on several occasion as the workstation was moved, the systems collided, spilling water over the entire contents of the system. Given the financial and safety consequences of these events, this solution was abandoned.

The next solution exploited a cylindrical mount designed to support an intravenous (IV) pole. The mount was positioned at the foot of the bed, on the right side. An LCD monitor pole with monitor arm was fit into this mount, enabling the participant to see the contents on screen. The tower for the computer system was set up in a corner away from Kate’s bedside. This solution was abandoned after one month, as the wires running from the tower to the monitor posed a safety hazard. Furthermore, the mounting system constrained the diameter, and therefore the strength of the pole supporting the monitor; after several weeks, the pole had bent to an alarming angle towards the participant.

Subsequently, the LCD monitor was removed, and the visual output of the computer was displayed on Kate’s bedside television. The tower was set up in an unoccupied corner of her bedroom, and wires connecting the tower to the television were secured along the wall. The final layout of the bedside access solution is illustrated in Figure 5-2. After several months of testing, this system was informally evaluated and approved by all stakeholders, as it satisfied both the constraints of the physical space, and Kate’s preferences.
Figure 5-2  Layout of the participant’s bedroom. The components of the access solution are shaded – the CPU was under the table beside her closet, and the computer display appeared on the television on the mobile table by her bed.

5.4 Measurement

5.4.1 System and human factors

To evaluate system and human factors of the access solution, we adopted measurement tools from the International Organization for Standardization (ISO) 9241-9 standards document for “requirements for non-keyboard input devices” (Douglas, Kirkpatrick, & MacKenzie, 1999). These tools, which gauge the performance, comfort and effort of computer input devices, were previously deployed in the evaluation of computer access solutions for students with quadriplegic athetoid cerebral palsy (Man & Wong, 2007).

The first part of the ISO 9241-9 evaluates system factors, namely, the movement time and the accuracy that a user is able to achieve with a non-keyboard pointer interface system. Based on Fitt’s Law, the test combines measures of distance to the target (D) and effective width of the target (\(W_e\)) with movement time (MT) to produce a measure of throughput (TP) according to the relationships outlined in equations (1)-(3) (Douglas et al., 1999), where SD represents the
standard deviation of the selection coordinates, and $ID_e$ represents the task’s effective index of difficulty.

$$TP = \frac{ID_e}{MT}$$  \hspace{1cm} (1)$$

$$IE_e = \log_2\left(\frac{D}{W_e + 1}\right)$$  \hspace{1cm} (2)$$

$$W_e = 4.133SD$$  \hspace{1cm} (3)$$

In a study evaluating the effectiveness of the different parts of the ISO 9241-9, MacKenzie et al determined that the one-direction task did not yield significant results (Douglas et al., 1999); consequently, in this study, we focused only on the multi-directional tasks to evaluate system factors. To this end, a two-dimensional array of targets was created to test the system performance for the participant; an example of these targets is depicted in Figure 5-3.

**Figure 5-3** An example of the targets created based on the ISO 9241, Part 9 Standard to test system performance. The individual was asked to target the shaded circle.
Eight different circles were presented to the user, who was told to use her computer access solution to click on the highlighted circle. The XY mouse began scanning the screen at the point marked (X) in Figure 5-3, and Kate used her tongue switch to stop the mouse when it reached the highlighted circle. The eight circles spanned a range of distances required for equation (2); varying widths were achieved by presenting four different sized circles, for a total of 32 trials. Within the 32 variations of the two-dimensional systems test based on Fitt’s law, eight different effective widths were presented to the user, as calculated with equation (3). These widths were representative of typical navigation requirements on a computer screen displaying the QualiWorld Software, and are presented in Table 5-1.

**Table 5-1** Effective widths ($W_e$) presented to the participant.

<table>
<thead>
<tr>
<th>0.66</th>
<th>0.99</th>
<th>1.69</th>
<th>1.82</th>
<th>2.03</th>
<th>2.73</th>
<th>3.67</th>
<th>4.22</th>
</tr>
</thead>
</table>

Kate used the XY-mouse to complete this part of the assessment. Consequently, all distances were measured with the start point at the top left corner of the screen where the XY-mouse began scanning, and with the end point being the coordinates that the participant finally selected. These trials were presented in a random order; Kate’s movement time (MT) and accuracy (0 = did not hit the target, 1 = clicked on the target) were recorded.

Human factors were evaluated using the ISO 9241-9 questionnaire that is comprised of questions about the subjective levels of comfort with and requisite effort in actuating a computer access solution. Responses were measured on a 7-point interval scale (International Organization for Standardization, 2000).

### 5.4.2 The Canadian Occupational Performance Measure (COPM)

The Canadian Occupational Performance Measure (COPM) is designed to detect changes in a client’s self-perception of occupational performance over time (Law et al., 1990). The tool measures users’ perceptions of their performance at an occupation, and their level of satisfaction
with this performance ability. Changes in performance and satisfaction scores of 2 or more points between assessment and reassessment are considered clinically significant (Law et al., 1998). In Kate’s case, we used the COPM to measure her performance and satisfaction with her use of a computer. An occupational therapist conducted the COPM at two times; we define Time 1 to be the time just before the computer access solution was introduced, and Time 2 to be two months after the solution had been introduced to Kate. Between Time 1 and Time 2, she was given the opportunity to use her computer access solution as often as she wished.

### 5.4.3 Frequency and type of computer usage

At Time 2, Kate was also asked to record how often she used her computer and for what purposes, over the course of a typical week. This information was gathered to capture her patterns of computer usage, and to compare these with her original goals for the computer access solution. Kate’s primary caregiver logged this information at the end of each day over a one week period.

### 5.4.4 Typing speed and accuracy

At Time 2, Kate’s typing speed and accuracy were also tested. She had become comfortable with a row-column scanning (R. C. Simpson & Koesten, 1999), with a scanning speed of 1.5 s. She was asked to type the sentence “My computer’s name is Bubbles.” complete with capitalization and punctuation, and also to type out the letters of the alphabet, in order, with a space between each letter. The number of switch activations and the time required to select each letter, the number of ‘missed’ selections, and the number of selection errors were recorded.

### 5.4.5 Semi-structured interview

Finally, at Time 2, Kate was asked to participate in a semi-structured interview to assess her level of satisfaction with the solution, and to garner her opinions on what she liked and what could be improved. The interview questions encouraged her to compare the computer access solution to those that she had previously tried, and to reflect on the importance of computer access, possible improvements and desirable features of the system, and the perceived impact on her lifestyle. The full transcript of the interview is presented in Appendix 1 of this thesis.
5.5 Results

5.5.1 System and human factors

In the two-dimensional Fitt’s Law test from the ISO 9241-9, the participant achieved an average throughput of 1.03 bits/s and an average accuracy of 87.5%. The values and ranges of the variables calculated during this assessment are presented in Table 5-2.

Table 5-2 Results of the ISO 9241-9 system assessment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to target (D)</td>
<td>30.1 cm</td>
<td>21.8 cm</td>
<td>38.9 cm</td>
</tr>
<tr>
<td>Index of difficulty (ID)</td>
<td>19.6</td>
<td>7.57</td>
<td>38.9</td>
</tr>
<tr>
<td>Movement time (MT)</td>
<td>19.9 s</td>
<td>14.2 s</td>
<td>27.5 s</td>
</tr>
<tr>
<td>Throughput (TP)</td>
<td>1.03 bit/s</td>
<td>0.34 bit/s</td>
<td>2.62 bit/s</td>
</tr>
</tbody>
</table>

On each of the questions evaluating the level of comfort and effort associated with the computer access solution, Kate consistently chose the highest rating. Specifically, these ratings indicated that she was very comfortable with the force required for actuation, and that she perceived the operation as very smooth and very low effort, very accurate and acceptable in operation speed, and very comfortable and very easy to use. Kate also indicated that there was no fatigue of the finger, wrist, arm, shoulder or neck. Given the specific nature of her access solution, the questionnaire also assessed the level of fatigue in her tongue; she indicated that there was none at this site either.

5.5.2 The Canadian Occupational Performance Measure (COPM)

The results of the pre- and post- COPM measures of the participant’s performance and satisfaction with her computer access solution are presented in Table 5-3.

Table 5-3 COPM results.

<table>
<thead>
<tr>
<th>Subscale</th>
<th>Time 1</th>
<th>Time 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance: Ability to use a computer</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Satisfaction: Ability to use a computer</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>
At Time 1, Kate reported that she was unable to use the computer, and not satisfied at all with her level of ability. At Time 2, she reported using the computer almost everyday for e-mail, internet and writing, that she was extremely happy about her current computer use and that she had developed an interest in learning about her computer. The changes in performance and satisfaction scores between the pre and post measure are considered clinically significant (Law et al., 1998).

5.5.3 Frequency and type of computer usage

The daily documentation of frequency and type of computer use at Time 2 are summarized in Table 5-4. On average, she used the computer for 8.4 hours per day.

Table 5-4 Frequency and type of computer use over a 1-week period.

<table>
<thead>
<tr>
<th>Day</th>
<th>Did you use your computer today?</th>
<th>For what purpose?</th>
<th>For how long?</th>
<th>Total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Checking e-mail</td>
<td>NA</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Writing e-mail, arranging transportation</td>
<td>7:40–11:05</td>
<td>3 h 20 min</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>Checking e-mail</td>
<td>7:15–10:00</td>
<td>4 h 45 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Music</td>
<td>13:00–15:00</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>E-mailing</td>
<td>9:00–22:00</td>
<td>13 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bible study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
<td>Checking e-mail</td>
<td>9:00–13:00</td>
<td>7 h 30 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13:30–17:00</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>Checking e-mail</td>
<td>9:00–13:00</td>
<td>11 h 30 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13:30–17:00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16:00–22:00</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Yes</td>
<td>Writing e-mail</td>
<td>9:00–13:00</td>
<td>10 h 30 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13:30–17:00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19:00–22:00</td>
<td></td>
</tr>
</tbody>
</table>

Average daily time: 8.4 h

5.5.4 Typing speed and accuracy

It took Kate 74 clicks, and a total of 7 minutes and 30 seconds to type the phrase “My computer’s name is Bubbles.” During the typing process, Kate took advantage of the built-in word prediction of the onscreen keyboard to minimize the number of clicks required to type each word, enabling her to select a letter with an average of 2.6 clicks. Without the word prediction, each letter required 3 clicks to select, and Kate was able to type the alphabet in 2 minutes and 35 seconds. Given system constraint of a 1.5 second delay between scanning options, the minimum possible time needed to complete this task was 2 minutes and 32 seconds. While these numbers demonstrate her proficiency in accessing the individual letters of the alphabet on her keyboard,
the time she required to type out the full sentence is more representative of her typical typing speed, as it accounts for format, punctuation, and spelling.

5.5.5 Semi-structured interview

During the semi-structured interview, Kate expressed a preference for her new tongue switch over the switches that she had previously tried. She reported that the sip-n-puff left her short of breath, and she remembered experiencing significant fatigue using the forehead and chin switches, both of which were non-issues with the tongue switch.

According to Kate, the most important reasons for having an access solution were: 1) to communicate and 2) to learn new things. She expressed interest in using her computer to do school work, to e-mail friends and family, and to “learn new things on the internet”. Asked about improvements that she would make to the system, she said that she would “make it more cool” and expressed interest in learning to use online chat rooms. Finally, she was asked about her overall impressions of the system, to which she replied “It’s a wonderful program. Very easy to work with. I like it a lot. It makes me more independent.”

5.6 Discussion

Within the International Classification of Functioning, Disability and Health (ICF) framework, the computer access solution is an environmental factor that may facilitate participation in life activities. In the following sections, the impact of the computer access solution on Kate’s well-being is interpreted in terms of the ICF domains. The numbers appearing in parentheses are the relevant ICF codes.

5.6.1 Expanding communication

The results of the speed and Fitt’s law tests indicate that computer access expanded Kate’s communication activities, specifically, writing messages (d345) and receiving written messages (d325). Prior to computer access, Kate’s participation in these activities was completely restricted. Indeed, enhancement of communication has been noted as a primary impact of access solutions for individuals with severe disabilities (Craig et al., 2005).

At first glance, Kate’s typing performance appears low. Using the multidirectional Fitt’s law test presented in the ISO 9241-9, able-bodied individuals were able to achieve an average throughput
of 2.15 bits/s using a joystick, in comparison to Kate’s average throughput of 1.03 bits/s (Douglas et al., 1999). In addition, the majority of able-bodied individuals would be able to type a five-word sentence in less than one minute whereas Kate needed 7 minutes and 30 seconds to complete this task. However, these numbers must be interpreted in the context of an individual who has never had any form of computer access. Assessments of Kate’s level of satisfaction with her access solution reveal that the speed she achieved was in fact, acceptable to her, and that it did not negatively affect her impression of the system. In response to the ISO 9241-9 question concerning the operation speed of the computer input device, Kate ranked her access solution ‘7’ on a 7-point scale, indicating that the throughput was acceptable. Her satisfaction with the system, in spite of these seemingly-low speeds was also reflected in the results of the COPM; at Time 2, she rated her satisfaction as ‘10’ on a 10-point scale, whereas at Time 1, before she had developed competency on the computer, her satisfaction level was a ‘1’. During the semi-structured interview, the speed of the access solution did not arise as an issue; even when asked about possible improvements, Kate suggested more “coolness”, rather than greater speed. Finally, Kate’s typing rate of approximately 3.5 letters per minute is on par with rates documented for typing by single-switch scanning of QWERTY on-screen keyboards (Lin, Wu, Chen, Yeh, & Wang, 2008).

5.6.2 New opportunities for interpersonal interactions and relationships

Prior to the access solution, the only way that Kate could connect to her social network was to wait for a nurse or her personal care worker to put the telephone by her head and dial a number for her. Furthermore, if the phone rang, she would not be able to answer the call unless there happened to be someone at her side. Thus, social interactions with family and friends could not be spontaneously initiated. The access technology however created new opportunities for Kate to nurture family relationships (d760), and informal relationships with peers (d7504) and friends (d7500). From the week long log of computer usage and the qualitative interview, it is clear that the solution allowed her to initiate and sustain interaction with family and friends through email. She was able to independently compose and send e-mails, and to open and read the replies she received. This enhanced interaction with family and friends echo the findings of Drainoni et al. (Drainoni et al., 2004), who report significant associations between social integration scores and internet usage in individuals with SCI.
Over the course of a typical week, Kate’s one consistent daily activity was to check and compose e-mail. She reported: “I’ve been on it [the computer] all day, every day, checking my e-mail, writing back. If I didn’t have the computer, I’d be bored.” Kate’s high frequency of computer usage and primary activity of emailing is consistent with recent studies examining the pattern of computer and internet usage by individuals with spinal cord injury (Drainoni et al., 2004; Goodman et al., 2008).

5.6.3 Facilitating education, leisure and spiritual activities

Prior to the access technology, Kate learned only what others chose for her to learn, and what others believed that she might find interesting. Computer access gave Kate the unprecedented ability to search for things of interest to her, and to direct the process of learning. When asked what she wanted to use her computer to do, she responded: “I want to learn new things on the internet.” In this way, the access technology facilitated opportunities for informal education (d810) at the bedside. This observation resonates with previous research that has identified new educational opportunities for people with disabilities as a key benefit of internet access (Drainoni et al., 2004).

Kate used her computer access for independent leisure activities (d920) such as reading and surfing the internet, the latter being a key activity identified by Houlihan et al. (Houlinhan, Drainoni, Warner, Nesathurai, & Wierbicky, 2003) in patients with SCI once granted internet access. Kate’s competence in surfing the internet is reflected in her unrestricted response to the question of what she went online for: “Searching for different places to live, different schools… anything!” Her access technology even created an accessible setting for spiritual development (d930) as she reported using her computer for Bible study.

When she was asked about the specific things she liked about the system, she reported: “It drags, and I can type, and I can save, and I can change the font, format, colour and underline…”, indicating her growing proficiency in using the word processor. Evidence from other studies of individuals with SCI (e.g.,(Kruse et al., 1996)) suggest that Kate’s newly developed computer skills would facilitate her participation in higher education (d830) and her opportunities for eventual employment (d850), although these benefits had yet to be demonstrated at the time of writing.
In summary, the access technology expanded Kate’s activities and participation in life situations, leading to an overall growth in independence. This heightened independence was not simply due to a change in functional ability, as often measured by professionals, but also attributable to the expansion of her personal and social freedoms (M. J. Scherer, Gray, Quatrano, & Lieberman, 1996). Kate recognized this effect, commenting that “It [computer access] makes me more independent”.

5.6.4 Environmental factors

Prior to the access technology, the demands of the environment outweighed Kate’s functional abilities, such that she could not perform the tasks of typing, reading emailing or surfing the internet. From an occupational science perspective, one can interpret the introduction of the access technology as a change in the physical environment which redresses the balance between the person, environment and occupation (Letts, 2003). From an ICF perspective, the access technology is an environmental factor which reduced the gap between performance and capacity and is thus a facilitator of the aforementioned activities.

It is important to note that the ICF concept of environmental context is much broader than just the physical environment. In a recent, ICF-inspired review of communication between patients with communication disability and healthcare providers, O’Hallaran et al. (O’Halloran, Hickson, & Worrall, 2008) identified a host of environmental facilitators and barriers, including, caregiver knowledge about disability and communication strategies, caregiver attitudes, physical factors in the hospital environment, and, hospital services, systems and policies. Likewise, from their interview of 136 patients with SCI, Lysack et al. (Lysack, Komaneccky, Kabel, Cross, & Neufeld, 2007) implicated the natural (physical) environment, government policies, transportation and health services as the chief barriers to community integration after SCI while Whiteneck et al. (Whiteneck et al., 2004) pinpointed the natural environment, transportation, “help at home” and “available information” as barriers to participation after SCI. Therefore, Kate’s access technology only directly modulated one component of the environmental context, namely, the physical elements of the hospital environment.
5.6.5 Access development approach

The development of Kate’s computer access solution followed a person-focused model of matching an individual to an assistive technology as opposed to the traditional people-focused model (M.J. Scherer, 2002). From the initial stages, Kate was consulted regarding her goals, expectations of the access solution, and her personal preferences. The client-focused process of establishing computer access allowed Kate to exercise her personal choice and to imprint her “personal touch” on the final solution, affordances described by Scherer in transitioning from a medical to a social model of service delivery (M.J. Scherer, 2002). Other person-focused case studies relating to the provision of access have also been detailed in the literature (e.g., (Bache & Derwent, 2008)).

Sparks emphasizes that the only ‘viable’ measure of success of an assistive technology intervention is the ability to function successfully in ‘real world’ situations (Sparks, 2000). In this particular case study, the constraints of Kate’s physical environment (i.e., hospital room) required the utmost attention to minimize the risk of abandonment. In fact, many elements of the ICF personal and environmental context – the access site, the software, the positioning of hardware within the room, the configuration of furniture, appliances and medical equipment, Kate’s posture, her motor ability, hospital building and safety policies, the level of computer proficiency of her caregivers, her financial resources – all had to be mutually compatible to achieve a usable solution. With the person-focused approach, we are more likely to ensure that individuals with severe disabilities are outfitted with assistive technologies that fit their individual needs and lifestyles.

5.6.6 Need for access research

Before the introduction of computer access, Kate was not without the ability to communicate; she had the ability to speak clearly and to express her needs and preferences. Computer access dramatically augmented her opportunities for participation in life activities. How much more profound the impact would be for an individual without a similar baseline communication ability? At present, clinically available access pathways depend largely on somatic muscle activation, leaving many individuals without a means of communication (Tai et al., 2008). This population includes individuals who are locked-in as a result of late-stage amyotrophic lateral sclerosis or brain stem strokes, as well as individuals with excessive involuntary movement (e.g.,
athetoid cerebral palsy), general hypotonia or severe muscle spasticity (e.g., spastic quadriplegic cerebral palsy). The results of this study encourage the hastening of access research and development for this often-invisible population.

5.6.7 Limitations

The positive findings of this case study must be interpreted in light of the limitations of its design. While a large range of both objective and subjective measures are employed in attempts to maximize the internal consistency of the study results, it is possible that the results are inflated due to Kate’s desire to give positive feedback to the researcher’s efforts to outfit her with an access solution. Future work examining the impact of introducing computer access to other individuals with severe and multiple disabilities, in different environments and at various stages of life must be conducted to assess the external validity of these study results.

This research was conducted as a case study of one specific intervention. While utilizing a single subject research design (SSRD) would have increased the rigor of the results, none of the range of SSRD options was suitable for this particular situation. As there was only a single subject and a single, binary intervention, multiple baseline design, alternating treatment design and changing criterion design (Horton & Miller, 1994) were all not feasible. The remaining option was reversal design, which the researchers decided not to use for ethical reasons.

Finally, this study only takes into account Kate’s experiences and perspectives on the introduction of a computer access solution. As computer access has been demonstrated to affect an individual’s social interaction and communication, and as Kate’s top priority in acquiring computer access was to communicate with her social network, further insights into the effects of this solution could be garnered by interviewing Kate’s friends and family. Gathering data from this source may also address any bias introduced into the reported results by Kate’s subjective experience of the solution, and provide further understanding of how computer access affected her interpersonal relationships and participation in life activities.
5.7 Conclusion

This paper presented a case study of a 20 year old female with quadriplegia who was outfitted with a computer access solution realizing a tongue-driven binary switch to access the internet, word processing and e-mail. The participant’s goals and the constraints of her real-world environment were considered throughout the design process. Two months after the introduction of the access solution, qualitative and quantitative measures indicated the acquisition of a functional level of single-switch typing, the expansion of everyday activities, particularly in the areas of communication, leisure and education, and a perceived, significant increase in independence. The purpose of this study was to assess the outcomes (e.g. effects on life habits, mood) of giving a disabled child the ability to interact with his or her built environment. The results clearly illustrate that a change in the ability to interact with the built environment affected this individual over multiple aspects of the activity and participation domains of the ICF. In order to effectively measure this effect, a diverse set of measurement tools were employed, and the results were triangulated to determine the overall effect on Kate’s wellbeing. While Kate was severely limited in her physical abilities, her ability to verbally express her opinions and preferences was not impaired. Children with profound disabilities do not share Kate’s verbal ability, but may be similarly impacted by a change in their ability to interact with their built environment, as their physical abilities are comparable to Kate’s. Consequently, it is important to employ a broad range of adapted assessment tools that target the multiple areas that may be potentially affected by this changed interaction, as illustrated in this study. The effect of environmental access had very significant outcomes on Kate’s life habits; the effect of a new mode for person-environment interaction has the potential to be even greater for individuals with no current means of engaging in this interaction. Future research assessing these outcomes with children with profound disabilities must address the multifaceted aspects of activity and participation illustrated in this study for the effect of new interaction modalities to be fully understood.
6 Theme 2 Variation 2: The Social Environment I

Physiological and Emotional Responses of Disabled Children to Therapeutic Clowns: A Pilot Study

Having established the scope of the effect of changes in the environment in the previous variation, this variation assesses the physiological, behavioural and emotional effects of changes in the social environment on individuals with profound disabilities. The first movement of this Variation examines the effect of introducing a social catalyst – a Therapeutic Clown – into the environment of individuals in a long-term health care setting. The study design and methodology address the challenges of working with the physiological signals of the profoundly disabled that were raised in Theme 1, variations 1 and 3. The necessity of using physiological signals as a medium for environmental interaction for the profoundly disabled is clearly illustrated in this movement, and the study presents a platform through which the effects of other environmental interventions for the target population can be effectively assessed.

6.1 Abstract

This pilot study examined the effects of Therapeutic Clowing on inpatients in a paediatric rehabilitation hospital. Ten disabled children with varied physical and verbal expressive abilities participated in all or portions of the data collection protocol. Employing a mixed-method, single subject ABAB study design, measures of physiological arousal, emotion, and behavior were obtained from eight children under two conditions – television exposure and therapeutic clown interventions. Four peripheral autonomic nervous system signals were recorded as measures of physiological arousal; these signals were analyzed with respect to measures of emotion (verbal self reports of mood) and behavior (facial expressions and vocalizations). Semi-structured interviews were completed with verbally expressive children (n=7) and nurses of participating children (n = 13). Significant differences among children were found in response to the clown intervention relative to television exposure. Physiologically, changes in autonomic nervous system signals occurred either more frequently or in different patterns. Emotionally, children’s (self) and nurses’ (observed) reports of mood were elevated positively. Behaviorally, children exhibited more positive and fewer negative facial expressions and vocalizations of emotion during the clown intervention. Content and themes extracted from the interviews corroborated these findings. The results suggest that this popular psychosocial intervention has a direct and positive impact on hospitalized children. This pilot study contributes to current understanding of the importance of alternative approaches in promoting well-being within healthcare settings.

6.2 Introduction

Since therapeutic clowning began in North America in 1986, it has become a popular practice in acute and rehabilitation hospitals worldwide ("Big Apple Circus," 2009; "Clowns in Hospitals," 2009; "A history of Caring Clowning in Canada," 2009; "Novel ideas: medical clowns for premature infants," 2009; Oppenheim, Simonds, & Hartmann, 1997) and increasingly is thought to play an important complementary role in healthcare (Koller & Gryski, 2008; Linge, 2008; Oppenheim et al., 1997). In contrast to the more familiar circus clown whose goal is to entertain, Therapeutic Clowns aim to promote patients’ well-being by supporting their expressions of control and emotion using pleasurable and playful techniques. By creating contexts that enable individualized, improvisational, often humorous social exchanges, Therapeutic Clowns alter the social and physical hospital milieu to enhance the physical and mental well-being of patients and
care providers (Koller & Gryski, 2008; Linge, 2008; Masetti, 1997, 2003; Oppenheim et al., 1997; Schwebke & Gryski, 2003).

Studies of therapeutic clowning have shown that this intervention facilitates verbal and non-verbal communication (Linge, 2008; Masetti, 2003); improves mood and attitude (Battrick, Glasper, Prudhoe, & Weaver, 2007; Koller & Gryski, 2008; Weaver, Prudhoe, Battrick, & Glasper, 2008); increases expressions of emotion such as laughter, joy, and humour (de Lima, Azevedo, Nascimento, & Rocha, 2009; Higueras et al., 2006; "Humour for good health in the ED and CAHU (The Clown Doctor project)," 2009; Linge, 2008; Wild, Wetzel, Gottwald, Buchkremer, & Wormstall, 2007); supports empowerment and active role-reversal (de Lima et al., 2009); and is perceived as a valuable complementary therapy by patients, families, and care providers (Battrick et al., 2007; Higueras et al., 2006; "Humour for good health in the ED and CAHU (The Clown Doctor project)," 2009). While these results are encouraging, they must be interpreted with caution due to the limitations of their predominantly qualitative or evaluative study designs. Studies employing experimental designs with children have focused exclusively on the effectiveness of goal-directed clowning to distract from pain and stress prior to or during invasive medical procedures. The results of these studies are mixed and understanding limited to acute settings (Canto et al., 2008; Golan, Tighe, Dobija, Perel, & Keidan, 2009; Gorfinkle, Slater, Bagiella, Tager, & Labinsky, 1998; Vagnoli, Caprilli, Robiglio, & Messeri, 2005). Hence, understanding of how therapeutic clowning affects the physical and mental well-being of hospitalized chronically ill and/or disabled children and their care providers is limited.

Children in long-term rehabilitation settings experience far more than invasive medical procedures; prolonged restricted activities, disempowerment, lack of personal control, and lengthy separations from their families contribute greatly to their stress and anxiety (Bossert, 1994; Hart & Bossert, 1994). Although the effectiveness of therapeutic clowning in enabling children to cope in this context is unknown, this intervention is likely to have significant positive effects. This hypothesis is supported by studies that have shown that therapeutic clowning enhances emotional and behavioural responses (Battrick et al., 2007; de Lima et al., 2009; Higueras et al., 2006; "Humour for good health in the ED and CAHU (The Clown Doctor project)," 2009; Koller & Gryski, 2008; Linge, 2008; Weaver et al., 2008; Wild et al., 2007). Positive changes in emotional responding arising from humour and laughter have been correlated with increased pain thresholds and immunity, and inversely correlated with stress hormone levels.
Gathering data to validate these effects in long term care settings, however, is complicated by the fact that many children have a variety of conditions that prevent them from responding in ways that are typical of nondisabled children. These conditions include severe cerebral palsy, traumatic brain injury, or brainstem stroke, and render many unable to move, gesture, or speak. Hence, measures that rely on speech, typical movements, or invasive techniques like blood sampling are neither feasible nor ethically justifiable (Dillon & Carr, 2007; Murphy, Tester, Hubbard, Downs, & MacDonald, 2005; Rabiee, Sloper, & Beresford, 2005). As a result of these challenges, such children are often excluded from research participation. However, recent research indicates that autonomic nervous system (ANS) or physiological signals can be successfully correlated with emotional states and thus can provide an alternative and non-invasive response measure (Bauer, 1998; Blain, Chau et al., 2008; Collet, Vernet-Maury, Delhomme, & Dittmar, 1997; Picard et al., 2001). Given the importance of inclusivity to our understanding of best therapeutic practice, the goal of this pilot study is to investigate physiological signals as a measure of responsiveness to arts-based interventions, specifically, therapeutic clowning.

Emotions modulate many processes controlled by the ANS including posture, skin temperature and moisture, respiration, and muscle tension (Bauer, 1998; Blain, Chau et al., 2008; Collet et al., 1997; Picard et al., 2001). When anxious, hands become cold and clammy, hearts race, and breathing becomes shallow and rapid. These changes arise from changes in electrodermal activity (EDA), skin temperature, respiration, and blood volume pulse (BVP). More specifically, EDA is a measure of the electrical conductance of the skin. Changes in EDA occur as a result of cholinergic stimulation of the sweat glands, causing them to release ion-rich sweat, thus increasing the overall conductivity (Boucsein, 1992; Vetrugno et al., 2003). Fingertip skin temperature is influenced by the cutaneous microcirculation of the hand. Among the fingertip vascular structures are anteriovenous anastomoses, which are innervated by sympathetic nerve fibers that react to stimulation of the autonomic nervous system (Hales, 1985). The respiratory and cardiovascular systems are dually innervated by both branches of the autonomic nervous system; stimulation from the sympathetic branch causes increased functioning in both systems and stimulation from the parasympathetic branch reverses this behavior (Blain, Chau et al.,
These changes can be spontaneously, reflexively, or voluntarily generated by a variety of internal or external arousal stimuli. The interested reader is referred to (Blain, Chau et al., 2008) for a more detailed description of physiological responding.

In 1983, Eckman demonstrated that five measures of the ANS (heart rate, left and right hand temperatures, EDA, and forearm muscle tension) could distinguish between six emotional states: surprise, disgust, sadness, anger, fear and happiness (Ekman et al., 1983). More recently, in the field of affective computing, computers have been trained to classify ANS signals to distinguish among a variety of emotions. For example, Picard et al. (Picard et al., 2001) used facial muscle tension, heart rate, skin conductance and respiration to distinguish between self-reported emotions (neutral, anger, hatred, grief, platonic love, romantic love, joy and reverence) to an accuracy of 81%. Similarly, Katsis et al. (Katsis, Ganiatsas, & Fotiadis, 2006) used the same set of signals to distinguish between high stress, low stress, disappointment, euphoria and neutral states to an accuracy of 86%. These findings suggest that ANS signals are reliable indices of specific emotions (Bauer, 1998; Blain, Chau et al., 2008; Christie & Friedman, 2004; Collet et al., 1997; Katsis et al., 2006; Lisetti & Nasoz, 2004; Picard et al., 2001).

However, while the results of these studies are promising, the physiological signals were collected from nondisabled adults in a controlled setting, where a constrained number of emotions were induced and validated through self-report and behavioural observation (Christie & Friedman, 2004; Collet et al., 1997; Ekman et al., 1983; Katsis et al., 2006; Lisetti & Nasoz, 2004; Picard et al., 2001). The ability for physiological signals to detect unconstrained, mixed sets of emotions in naturalistic environments is still under debate. This problem is further confounded when these signals are gathered from disabled children, whose physiological systems may respond with different patterns than nondisabled adults. Thus, to attempt to understand the effects of therapeutic clowning on disabled children experiencing prolonged hospitalization, we augmented their physiological signals with direct observations of their behaviours, self-reported mood, and third-party observations of interactions. Based on current understanding, we hypothesize that children would demonstrate positive, differential physiological, behavioural, and emotional responses to Therapeutic Clowns.
6.3 Method

6.3.1 Setting and Design

This study was conducted in a large urban paediatric hospital that provides long term rehabilitative and complex continuing care to children with a range of physical, cognitive, and/or developmental congenital or acquired disabilities. Many of the children have conditions that affect the somatic branch of their ANS, causing decreased or involuntary muscular control, which in some cases renders them unable to move or to speak. For these children, many physical and physiological modalities by which emotion can be expressed are differently affected or rendered uninformative. Given the potential for idiosyncratic patterns of responding, between and/or within-subject group designs were not appropriate – hence a single subject research design was adopted (Logan, Robbin, Harris, & Heriza, 2008). A mixed methods approach was used to capture the children’s physiological, behavioural, and emotional responses to therapeutic clowning.

6.3.2 Participants

Fourteen inpatients between the ages of 4 and 21 years were recruited to participate in this study. Ethical approval was received from the relevant institution, and written consent was obtained from children and/or their guardians. Children were excluded if they had a visible breach of the epidermis or dermis on their arms or their hands. According to these criteria, and as a result of equipment malfunction (1), drop-out (1), experimenter error (1), and collection difficulties related to small hand size (2) and/or spasticity (1), objective quantitative data from 8 inpatients (4 male, mean age = 10.7 years, $SD = 5.0$) were retained. Five of these children were verbally expressive and had the cognitive skills needed to contribute self-report and interview data. An additional 2 verbally expressive children from the total sample also participated in the interview yielding a sub-set of 7 participants (4 male, mean age = 10.7 y, $SD = 2.9$) for this component. Thus, the final sample comprised 10 children with primary diagnoses that included Arterio-venous Malformation, Guillan-Barré Syndrome, Macrophage Activation Syndrome, Transverse Myelitis, Cerebral Palsy, and Encephalopathy. While one child had been hospitalized for over 5 years, the average length of hospitalization for the remaining nine children was 52 days ($SD=37$). Six of the children had been exposed to therapeutic clowning prior to participating in this study.
6.3.3 Intervention

As part of an established professional Therapeutic Clown program, Dr. Flap and Ricky visit three inpatient units of a 75 bed facility two afternoons a week in a duo-clown partnership. Dr. Flap has performed professionally as clown and actor for 17 years in theatre and circus realms; Ricky has performed professionally as an actor for over 10 years. They have also performed for 3 and 5 years respectively as therapeutic clown practitioners in large urban pediatric hospitals. Costumed in only a red nose and equipped with a multitude of tools (including music and rhythm, movement and physical comedy, storytelling and role-reversal, magic tricks and games), the clowns endeavor to empower children during short individualized visits (e.g., 10-15 min).

A children’s television program was selected as a familiar control stimulus that provided similar audio-visual stimulation (e.g., loud, colourful, musical, humorous, etc.), permitted individual choice, and that would be accessible to all children irrespective of cognitive abilities or developmental status.

6.3.4 Data Collection

Data were collected over 4 days of alternating interventions (ABAB); Table 6-1. On control days (A), children watched a television show of their choice, and on intervention days (B), children received routine therapeutic clowning interventions. The study took place in each child’s room at a consistent time to control for circadian rhythms in ANS responses. Prior to the commencement of this study, the clowns toured the units with mock physiological recording equipment to familiarize children. The research assistant further demonstrated the equipment and responded to concerns on the first day of data collection. For non-verbal children, a parent or a nurse familiar to the child assisted with set-up. No signs of distress or fear were noted among any of the participants.

During data collection, children were either comfortably seated or lying down and instructed to minimize their movements. Each session consisted of 20 minutes of data collection beginning with a five minute baseline rest period (0 min ≤ t ≤ 5 min), 10 minutes of the scheduled intervention (5 min ≤ t ≤ 15 min), and a five minute post-intervention rest-period (15 min ≤ t ≤ 20 min). The baseline rest period ensured children had acclimatized to the physiological recording equipment prior to the introduction of the intervention. The length of the intervention
window was predetermined by standard clowning practice and is consistent with similar studies examining change in physiological responding among children (Gilissen, Koolstr, vanlizendoorn, Bakermans-Kranenburg, & van der Veer, 2006; McManis, Bradley, Berg, Cuthbert, & Lang, 2001; Nagengast, Baun, Megel, & Leibowitz, 1997).

Table 6-1  Overview of study design

<table>
<thead>
<tr>
<th>Intervention (duration)</th>
<th>Period 1: Baseline (5 min)</th>
<th>Period 2: Intervention (10 min)</th>
<th>Period 3: Rest (5 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Rest</td>
<td>Television (TV)</td>
<td>Rest</td>
</tr>
<tr>
<td>B</td>
<td>Rest</td>
<td>Therapeutic Clowning (TC)</td>
<td>Rest</td>
</tr>
</tbody>
</table>

6.3.5  Measures

In recognition of the children’s diagnostic complexity and their diversity in verbal and physical expressive vocabularies, data collection tools were selected that enabled the inclusion of all inpatient children.

6.3.5.1  Physiological Responses

As outlined, EDA, skin temperature, respiration, and BVP are strongly associated with emotive responding (Christie & Friedman, 2004; Lisetti & Nasoz, 2004). These four physiological signals were collected with non-invasive sensors and the ProComp Infiniti ©, a data acquisition system from Thought Technology. To monitor EDA, 2 gel-less Ag/Ag-Cl sensors were attached to the medial phalange of the index and middle finger of the child’s non-dominant hand. To monitor BVP, an infrared sensor was loosely secured with velcro to his/her fourth finger, and to monitor skin temperature, a surface thermistor was attached to his/her fifth finger with breathable tape. Finally, a piezoelectric belt was comfortably positioned around the child’s thorax to monitor respiratory signals. The positioning of these sensors is illustrated in Figure 6-1. All sensors were sampled at a frequency of 256 Hz. Continuous-time recording was used during each 20 minute collection session to control for temporal variations and transient changes in the signals and to determine each child’s pattern of physiological responding (Hot et al., 1999).
6.3.5.2 Behavioural Responses

Six facial and vocal expressions that are commonly associated with emotions of a strong positive or negative valence were tracked by one of two trained observers for the duration of data collection. The observers had previous experience with disabled children; with data collection methods (physiological and observational); and completed a joint training session to ensure reliability in coding. Positive valence expressions included laughing and smiling while negative valence expressions included yelling (without smiling), sighing, crying, and grimacing (Green et al., 1997; Green & Reid, 1996). Each minute of the data collection period was divided into twenty second responses for a total of 60 intervals. The observer recorded the presence of behaviours during each 20 second interval.
6.3.5.3 Emotional Responses

Feeling Faces Cards © were used to facilitate verbal children’s self-report of mood (Beder, 2009). These cards present twenty exaggerated expressions of different valences on ethnically diverse male and female children’s faces. Each day, children were asked at \( t = 0, 5, 15, \) and 20 min to select the card(s) in response to the question “How do you feel right now?”

6.3.5.4 Verbal Responses

At the end of the four days of data collection, verbal children participated in a brief semi-structured interview. They responded to the following 5 questions:

1. How do you feel on the days when Dr. Flap and Ricky visit you?
2. How do you feel on the days when the clowns do not visit?
3. What things do you like about the clowns?
4. What things do you not like about the clowns?
5. What would you tell your friend/sibling about Dr. Flap and Ricky?

6.3.5.5 Nurses’ Observations of Children’s Responses

Thirteen nurses participated in short semi-structured interviews to explore their perceptions and experiences of therapeutic clowning and observations of clown-child interactions. They responded to the following question: “Do you think the children feel and/or behave differently when the clowns visit?”

6.4 Analysis and Results

6.4.1 Physiological Signals

The four physiological signals were analyzed using a custom-made multivariate change detection algorithm designed to detect patterns of physiological signal change; the interested reader is referred to (Blain, Kingsnorth, & Chau, 2010) for further details. For each physiological signal, a representative feature was extracted for every second of data collected. Features extracted during the initial five-minute rest period (Period 1) were used to describe the multivariate mean, range,
and variability of the pattern of physiological responding unique to that child while he/she was at rest. Features extracted during the subsequent ten-minute intervention period (Period 2) were compared against those generated during the resting state (Period 1). Time points in which the extracted features did not belong to the class of the child’s resting patterns were counted and characterized, such that the analysis of each intervention yielded two outcome measures: (1) the total number of outliers ($T$), in other words, the number of seconds where the child’s physiological signals did not fall within resting patterns, and (2) the average contribution of each physiological signal to the outliers generated during that intervention ($C_{avg}$).

Both outcome measures were compared between television and clown interventions using regression analyses (logistic and linear, respectively for $T$ and $C_{avg}$). To address intra-subject variability, a stringent criterion was adopted; children were classified as frequency responders if $T$ was significantly different between the two television control days and the two clown intervention days ($p < .05$). Similarly, children were classified as pattern responders if any of their physiological signals demonstrated a significantly different pattern of response (i.e., if $C_{avg}$ was significantly different) between the two television intervention days and the two clown intervention control days ($p < .05$). Classification was not exclusive; children could be classified as both a frequency and pattern responder.

Findings from the regression analyses are presented in Table 6-2. It is evident that no two children demonstrated the same pattern or combination of responsive physiological signals. All eight children experienced one or more significant physiological change in response to therapeutic clowning in comparison to watching television. The six classified as frequency responders all demonstrated significantly higher frequencies of arousal during Therapeutic Clown exposure relative to television exposure. Among the six children classified as pattern responders, there was variability in the dominating physiological signals and in the direction of change. For two, exposure to therapeutic clowning decreased their baseline levels of responding. For example, Participant 5 experienced a drop in fingertip temperature and a slowing of breathing rate. In contrast, Participants 1, 2, 6, and 7 all experienced increases in skin temperature either independently or in combination with another physiological signal.
Table 6-2  Results of the regression analyses of the ANS data.

<table>
<thead>
<tr>
<th>Participant</th>
<th>T</th>
<th>Cavg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BVP</td>
</tr>
<tr>
<td>1*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
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<td>3</td>
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<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Highlighted cells represent significant differences between AA and BB conditions ($P < 0.05$). Solid cells indicate a reduction in physiological responding while hatched cells represent an increase relative to baseline levels. *Denotes partial data set (i.e. AAB).

6.4.2  Behavioural Responses

Behavioural responses were obtained from 7 of the 8 children and a range of facial and vocal expressions were displayed. For each child, each behavioural response was normalized by taking the difference between the total frequency for Period 1 (see Table 1; n=15 intervals) and the average total frequency for Period 2 (n=30 trials/2) for each session. Logistic regression analysis was used to determine whether behavioural differences were significantly different ($p < .05$) between the television and clowning interventions.

As outlined in Table 6-3, 7 of 8 children demonstrated positive and negative behavioural expressions of emotion. Using a moderately stringent criterion, cells are highlighted for all children who displayed one or more pairs of significant differences in expressive behaviour between sessions ($p<.05$). Significant increases in smiling and laughing and decreases in grimacing were found. No differences between interventions were found for negative vocal expressions (i.e., yelling, crying, and sighing); in general, negative expressions of emotion were low in frequency.
Table 6-3 Results of the logistic regression analysis of behavioral responses.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Smiling</th>
<th>Laughing</th>
<th>Grimacing</th>
<th>Yelling</th>
<th>Crying</th>
<th>Sighing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
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<tr>
<td>2</td>
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<td>3</td>
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<td>X</td>
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<td>X</td>
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<td>4</td>
<td>X</td>
<td>X</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>7*</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>8</td>
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</tbody>
</table>

All cells marked by ‘x’ denote observed behaviors. Highlighted cells represent significant effects (P < 0.05); solid cells indicate a reduction in frequency of behavioral responding while hatched cells represent an increase relative to baseline levels. *Denotes partial data set (i.e. AAB).

6.4.3 Emotional Responses

To explore changes in emotion, each child’s mood report was assigned a positive or negative valence. The most common responses across the 4 data collection sessions were reports of being happy (n=22), content (n=8), excited (n=3), or surprised (n=3). Negative mood reports included being tired (n=12), bored (n=8), or hungry (n=3); no expressions of fear were reported. These emotions were reported individually or in combination (e.g., ‘happy and content’ or ‘tired and bored’). Changes in overall valence and strength prior to (t = 5) and after (t = 15) Period 2 were determined for each day. Table 6-4 displays the results of a visual inspection of these changes. Participants 3, 5, and 8 did not have a reliable means of communication and were unable to self-report, therefore are excluded from this table. Despite 4 missing cells on clown days among the verbal children, the overall trend demonstrated is a positive change in mood following exposure to the clowns and no change in mood following exposure to a children’s television show.
6.4.4 Self and Nurse Observation of Responses

The interview data were transcribed verbatim and analyzed using qualitative data analysis software ("NVivo8," 2009). Data were explored using a range of techniques including content analysis and testing of emergent themes. A coding scheme was developed based on the study’s goals and questions, as well as themes emerging from the interviews. Transcripts were coded for descriptive content, such as nurses’ descriptions of children’s behaviour, and children’s description of therapeutic clown behaviour. Coded texts were analyzed for patterns and themes that illuminated the children’s responses to therapeutic clowning.

6.4.5 Clown-Child Observations and Interactions

The children’s interviews yielded very positive descriptions of their responses to Therapeutic Clowning; 6 of the 7 verbal children said they feel ‘happy’, and 5 said they feel ‘excited’ when the clowns visit. On days when the clowns do not visit, 3 children said they feel ‘sad’, 1 is ‘bored’, 2 ‘happy’, and 1 child feels ‘ok’. It is noteworthy that when children expressed negative emotions, they did so within the frame of reference of the clown’s game; for example, two children described not liking specific clown behaviours: “Ricky is naughty and flooded the bathroom” (9); “…they don’t listen…they are bad. Sometimes Ricky misbehaves and I give him a timeout on the bed” (6). These reports indicate that the children are enthusiastically engaged with the clowns while simultaneously disapproving the clown’s naughty behaviour.
6.4.6 Nurses’ Observations of Children’s Responses

The nurses’ descriptions of children’s responses are also overwhelmingly positive. Almost all the words used by the nurses to describe the children’s moods when interacting with the clowns suggest increased energy, happiness, and excitement; and some nurses perceive the children to be more relaxed when the clowns are present. Some behaviour that nurses ascribed to the children were quite complex, such as deliberately manipulating the clowns, or pretending to feel an emotion as part of the play. Referring to a non-verbal child, one nurse said "Even if she doesn’t laugh or smile when they are right there singing, when they go to another child she will smile when they leave. Sometimes she pulls that on them too and they think she doesn’t want them, she will then smile, but she doesn’t want them to see that". When examined in the context of verbal children’s self reports about disciplining the clowns, and the clowns’ intent to give children power, this description may reflect children’s multilayered emotional experiences – such as enjoyment in expressing anger, or pleasure in acting bored.

6.5 Discussion

6.5.1 Impact of Therapeutic Clowns on Children in a Rehabilitation Setting

Despite their popularity, alternative and complementary health interventions such as therapeutic clowing are at risk of being cut in times of fiscal restraint. In the absence of empirical evidence supporting their benefits to physical and mental well-being, they are considered non-essential and difficult to justify. This study begins to address this need by determining the physiological, behavioural, and emotional effects of therapeutic clowing on children in a rehabilitation hospital.

Across all children, significant differences in patterns of ANS responses were found in response to therapeutic clowing as compared to exposure to a children’s television program. Although physiological measures were the only measure which could be ubiquitously obtained from all participants, the interpretation of these signals is entirely dependent on complementary measures of response. While previous work has demonstrated that physiological signals are emotion specific, the heterogeneity of this population yields individual-specific patterns of physiological change. This is clearly illustrated in comparing the results presented in Tables 6-2 and 6-3. While Participants 1, 2, 4, 5 and 6 all demonstrated greater positive behavioural changes in response to
therapeutic clowning than to television, no two children demonstrated the same patterns of physiological change. We can ascribe positive and negative valence to physiological responses that are accompanied by behavioural and/or verbal responses, but in the absence of this complementary information, we cannot accurately interpret these results. Despite the inter-subject variability in ANS response patterns, the direct and third-party observations of increased smiling and laughing, decreased grimacing, and positive changes in mood strongly suggest that the physiological changes observed can be considered to reflect positive responses.

These findings complement and expand current understanding of this popular arts-based intervention to include disabled children who are experiencing prolonged and/or repeated hospitalizations (Battrick et al., 2007; Canto et al., 2008; de Lima et al., 2009; Golan et al., 2009; Gorfinkle et al., 1998; Higueras et al., 2006; "Humour for good health in the ED and CAHU (The Clown Doctor project)," 2009; Linge, 2008; Vagnoli et al., 2005; Weaver et al., 2008; Wild et al., 2007). Furthermore, they demonstrate the value of using a broad spectrum of techniques and sources, especially for heterogeneous populations commonly encountered in rehabilitation hospitals. Only five participants were able to contribute all three types of data (i.e., physiological, behavioral, and verbal) as operationalized in the current study. The need to use a multi-pronged approach to facilitate the inclusion of profoundly disabled children may underlie the paucity of empirical research exploring their experiences of the world.

6.5.2 Interrelation Among Response Modalities

In addition to enhancing understanding of the effects of therapeutic clowning, our multi-pronged approach further highlights the inter-relationships among expressive modalities and the strength of triangulation. For example, nurses described an emotion to be present (such as happiness or anticipation), and when pressed to elaborate, described behavioural indicators such as flapping arms, concentrating more intently, or smiling. Thus, nurses perceived very clear connections between these children’s emotional and behavioural responses; one nurse even connected a child’s emotional state to physiological signals, and specifically referred to changes in respiration and blood oxygen saturation as indicators of the child’s pleasure in response to therapeutic clowning. These qualitative findings are consistent with understanding of emotion as a modulator of almost all forms of verbal and human communication (Picard et al., 2001). More importantly, they showcase the limits of conventional definitions of expressive behaviours.
As a result of the broad spectrum of impairments in our sample, the range of observed behaviours exceeded the six behaviours selected to represent overt expressions of emotion. For example, a significant response may be a muscle twitch in one child and a rapid and wild wheelchair ride in another child. Certainly, typical behaviours such as laughing, eye contact, and moving towards or following the clowns were described by many nurses, but other described behaviours that included flapping arms and legs, rolling around in bed, longer durations of directed eye-gaze, or making sounds. Further complicating interpretation of emotional expressions were reports suggesting that multiple emotions were experienced simultaneously, such as pleasure in feeling angry in the context of disciplining the clowns. By employing narrow indices of happiness and unhappiness, the full range of emotion-specific behaviours evidenced may not have been captured. Further work involving disabled and/or chronically ill children should move away from facial and vocal expressions of emotion typical of nondisabled children, and instead use responses that reflect the particular emotional expressions of individual children (Dillon & Carr, 2007).

6.5.3 Children with Severe and/or Multiple Disabilities

More broadly, findings from this study have implications for understanding how profoundly disabled children experience the world. Participants 3, 5 and 8 do not have a reliable physical or verbal means of expressing themselves and decoding their responses to stimuli is very difficult. The reader can get a clear understanding of how daunting this task is by reviewing the limits of the conventional measures of affect we employed. These children were not able to verbally report, either by interview or by choosing a Feeling Faces card, their mood or their perception of the clowns. Participant 8, in particular, either did not engage in normative expressions of emotion or his/her behaviour during the therapeutic clowning interventions was not significantly different from typical patterns. Although nurses expressed confidence in being able to ‘read’ the responses of these children – several answered “definitely” and “you can certainly tell” in response to questions about whether a movement or behaviour signified a given mood or desire – data from the conventional measures alone does not support their interpretations. This ‘knowledge’ is likely a function of the nurses’ extensive training in caring for such children and familiarity with their complex needs.
In the absence of overt and consistent displays of emotion or preference, it is easy for those not intimately familiar with these children’s idiosyncratic nuanced expressions to assume that they are non-responsive. Table 6-2, however, presents an alternate story – all three of these children were frequency responders – with significant increases in physiological responding to the Therapeutic Clowns that were not merely a function of audiovisual stimulation. Two children were also pattern responders displaying differential patterns of responding. Thus, in spite of a lack of evidence from conventional measures, the physiological data clearly demonstrated that therapeutic clowning had an effect on these children.

While the valence of these reactions remains unverifiable in the absence of overt behaviors or self-report, these results illustrate the value of using physiological signals as a means of garnering insight into the emotional state of children with profound and/or severe impairments. Furthermore, they enhance our understanding of the different ways people respond to their environments and broaden current definitions of participation and inclusion. For example, changes in physiological responding may be a means of determining preferences for meaningful and enjoyable activities among children with profound disabilities and ensuring varied social interactions, engagement, and positive stimulation -- factors that contribute significantly to positive emotions and quality of life (Hergenroder & Blank, 2009).

6.5.4 Strengths and Limitations

Although small sample sizes and heterogeneous populations are typically considered study limitations, we consider these circumstances as strengths. By employing a single subject research design, this pilot project was elevated from a case study to a rigorous experimental design. Normalization of the data relative to baseline for each data collection session further ensured that differences in responses were the result of the intervention and not a consequence of day-to-day changes in health status (e.g., pain, medication, lack of sleep, etc.) among the heterogeneous population. Multiple data sources and measures allowed for a triangulation of findings – a process of particular relevance for individuals with limited expressive modalities. Finally, continuous ANS recording avoided potential pitfalls associated with single time point recordings. While some information can be gleaned from the latter data collection approach, caution must be exercised in its interpretation, particularly with heterogeneous populations. EDA, for example, demonstrates temporal variation throughout the day, and is subject to the circadian rhythms of
the body (Hot et al., 1999). Furthermore, the salient information in EDA patterns can only be gleaned through continuous recording.

Although small in numbers, the current findings strongly suggest that the changes in physiological responding were not a function of audio-visual stimulation, expressive ability, or of a pre-existing relationship with the clowns – as significant differences were seen for all children. The possibility remains however that these changes are the result of a live interaction with another person. Identification of a suitable control for a therapeutic clown challenged the authors; in the end, selection of a children’s television show provided the greatest amount of control and consistency across participants. It should be noted that despite attempts to keep the presence of the observers neutral and unobtrusive, many of the children had a difficult time ignoring their presence and engaged them in conversation. Further, the third-party observations provided by the nurses suggests that the presence of therapeutic clowns on the unit changes the children’s behaviour and mood in ways that are not typically seen in other interactions between children and caregivers.

Future work should build on these strengths by replicating the current findings with a larger sample size to permit a more detailed exploration of physiological responding among disabled children under different environmental conditions. The inclusion of broader definitions and more sophisticated assessments of ‘non-traditional’ behavioural indices of emotion are strongly recommended to minimize observer bias and facilitate validation and interpretation of the ANS signals.
6.6 Conclusions

In recent years, there has been a rapid expansion of therapeutic clowning programs in healthcare settings. Despite the popularity of this intervention, there has been little systematic investigation of its effects. The current study is valuable in its efforts to address gaps in the literature. First and foremost, it is the first study to explore and demonstrate that therapeutic clowning has a direct physiological impact on children. Second, it expands the range of healthcare settings investigated in the literature to include rehabilitation and focuses on children with chronic conditions experiencing prolonged hospitalizations. Third, the behavioural, self-report and third-party observational data supports existing evidence that therapeutic clowning has an overall positive effect on mood and well-being – even on profoundly disabled children. These findings offer a promising platform to support the continued investigation of therapeutic outcomes among heterogeneous populations, and illustrate the effectiveness of using physiological signals to assess the effect of changes in the social environments on profoundly disabled children.
7  **Theme 2 Variation 2: The Social Environment II**

A Multivariate Classification Algorithm for Detecting Change in Physiological State

The second movement of this variation presents the multivariate classification algorithm that was used to detect significant change in physiological state in the data presented in the first movement, which assessed the effect of changes in the social environment on children with profound disabilities. This variation answers the question of how peripheral autonomic nervous system signals can be used to detect the effect of changes in the social environment in children with profound disabilities. Specific challenges regarding physiologically-mediated interaction between the person and their environment that were presented in Theme 1 variation 1, namely, the profound inter- and intra-subject variability of physiological signals, are explicitly address in the formulation and application of this algorithm.

7.1 Abstract

Change in the physiological state of an individual manifests on a systemic level; accurate detection of this change must account for its multivariate nature. Once identified, comparison of these changes both between and within individuals is challenging due to the significant inter- and intra-subject variability of physiological response patterns. This paper presents a multivariate classification algorithm for physiological signals that addresses this variability, and quantifies the change using two measures: intensity and pattern. These two measures enable the comparison of physiological changes within and between individuals, and reflect the objective measures developed from Lang’s theory of emotional state: arousal and valence. This method is illustrated through an application to autonomic physiological data collected from rehabilitation hospital inpatients while watching television and interacting with Therapeutic Clowns.

7.2 Introduction

The accurate detection of change in an individual’s physiological state has widespread application including bedside monitoring systems (Shah et al., 2008), ambulant monitoring of fragile-health individuals (van Halteren et al., 2004) and those under high-stress conditions (Senhadji et al., 2000), and communication with individuals with severe and multiple disabilities (Blain, Mihailidis et al., 2008). In the absence of physical activity and chronic health conditions, many physiological signals are established indicators of the state of an individual’s autonomic nervous system, including brain wave patterns (Birbaumer, 2006b), electrodermal activity (EDA) (Blain, Mihailidis et al., 2008; Boucsein, 1992), skin temperature (Kistler et al., 1998) and cardiorespiratory signals (B. C. Lacey & Lacey, 1980; Prkachin, Williams-Avery, Zwaal, & Mills, 1999). Significant efforts have been made to utilize these signals to detect changes in autonomic state. However, many of these efforts have been limited by the complex and dynamic nature of the physiological system. Physiological signals fluctuate with natural rhythms of the human body (Hot et al., 1999) and in a manner unique to each person (J. I. Lacey & Lacey, 1958) - the variability in physiological measurements between and within individuals is profound. In addition, changes in physiological state normally manifest on a systemic level, as opposed to simply within one specific physiological signal (Kutas & Federmeier, 1998). Efforts to date have addressed the problem of detecting change in physiological state by examining individual physiological signals independent of the others (e.g. electrodermal activity, heart rate).
and while many studies account for multiple physiological signals, the correlation between the signals often remains ignored (Cacioppo & Tassinary, 1990; Ekman et al., 1983; Katsis et al., 2006; Picard et al., 2001). Although the univariate classification problem has been extensively studied, existing classification algorithms do not formally represent the multivariate nature of the problem.

Further complicating the challenge of detecting physiological change is the lack of a reliable gold-standard against which to verify that a change in state has actually occurred. In the field of emotion recognition, for example, algorithms are trained by associating changes in physiological signals with self-report of or induced emotional state (Bauer, 1998; Bradley, 2001; Ekman et al., 1983; Kim, Bang, & Kim, 2004; Winton, Putnam, & Krauss, 1984). This standard approach for identifying emotion, however, has a number of limitations that include variability in how individuals interpret different emotions and the difficulty in inducing a pure emotional state (Picard et al., 2001). Furthermore, existing algorithms detect changes over an extended period of time; there does not exist a method for verifying moment-to-moment changes in an individual’s systemic physiological state.

Thus, there is a need to develop an objective estimation of change in physiological state. Efforts were undertaken in the 1970s to develop an objective measure of change in emotional state. Many theorists have proposed a biphasic organization of emotion (Dickinson & Dearing, 1979; Konorski, 1967). While patterns of emotional expression are highly varied, they are believed to arise from a simple, two-factor organization of affect into either appetitive or aversive stimulation (Cacioppo & Bernston, 1994). Research has demonstrated that a dimension of activation from calm to aroused accounts for substantial variance in subjective reports of emotion (Osgood, Suci, & Tannenbaum, 1957). Lang (Lang, 1998) merged these lines of theoretical development and postulated that two motivational systems exist in the brain, appetitive and defensive, and each can vary in terms of activation or metabolic arousal. Lang also categorized the indices of emotional expression in human beings as belonging to one of three reactive systems: (1) expressive and evaluative language, (2) physiological changes mediated by the somatic and autonomic systems, and (3) behavioural sequelae, such as patterns of avoidance or performance deficits (Lang, 1978). Applying this theory to expressive and evaluative language, Lang developed a two-dimensional measure of reported emotions, with level of arousal along one axis and valence along the next. Systems of calibrated stimuli, such as
the International Affective Picture System (Lang, Bradley, & Cuthbert, 1998), have been
developed from these objective measures in the scientific study of emotion. Reflecting the
efforts in this parallel field, we endeavour to apply Lang’s theory to the field of physiological
states and search for corresponding measures to quantify changes therein; specifically, we set out
to develop an algorithm that models the intensity (i.e. arousal) and patterns (i.e. valence) of a
change in physiological state.

In this paper, we develop an algorithm that examines four peripheral autonomic signals -
electrodermal activity, skin temperature, respiration patterns and blood volume pulse – for
multivariate changes that are indicative of a systemic change in physiological state. This
algorithm attempts to address existing gaps in the literature by both accounting for the
multivariate nature of change in physiological state, and by accounting for the profound inter-
and intra-subject variations in signal patterns over time. We begin the methods by formulating
the multivariate classification algorithm (section 7.3.1); proceed to ground this algorithm in
Lang’s theory of emotional states and illustrate how it can be used to compare physiological
reactions to different stimuli (section 7.3.2); and finally offer an application to physiological
signals generated by children from a rehabilitation hospital when engaged in the activities of
watching television and interacting with Therapeutic Clowns (section 7.3.3). The results of the
proposed algorithm on this data are presented and discussed.

7.3 Methods

7.3.1 The Multivariate Classification Algorithm

7.3.1.1 Overview of the Algorithm

Physiological data gathered for analysis with this algorithm are collected under the paradigm that
change in physiological state must be measured against a baseline state that is re-calibrated at
each occasion of data collection. Accordingly, the four aforementioned physiological signals are
recorded while an individual is at rest and continue to be recorded while a stimulus is introduced
immediately following this rest period. A salient feature is extracted from each physiological
signal on a second-by-second basis and used to populate a 4-dimensional space representative of
the individual’s baseline state. This space is transformed into one of unit variance along each
dimension, where the boundaries of this baseline state are then defined. Physiological signals
recorded during each second of exposure to the stimulus are compared against the boundaries of this baseline state; if they fall outside the boundaries, the participant is assumed to have undergone a change in physiological state from baseline. The number of outliers, and the contributions of each physiological signal that constitute each of these outliers, are recorded to quantify this change.

7.3.1.2 Feature Extraction

Data collected according to the paradigm required by this algorithm are presented in Figure 7-1. In both Condition A and Condition B, physiological signals depicted before the vertical line represent the individual’s resting physiological state, while signals depicted after the vertical line are collected as a stimulus is being presented to the individual.

![Figure 7-1](#)

**Figure 7-1** Raw physiological signals collected over a 5 minute baseline period, followed by a 10 minute intervention period.

For each second of data collected, the individual’s overall state was represented by a 4-dimensional feature vector consisting of one feature derived from each physiological signal. The process of feature extraction is described briefly herein.
**Electrodermal Activity:** The raw electrodermal activity (EDA) signal was filtered using a moving average filter over a one-second window to remove high frequency noise. Previous studies have shown that the centroid of the slope within a one-second window is correlated to an individual’s mental state (Blain, Mihailidis et al., 2008); this feature was calculated for each second of the recorded data. **Temperature:** The rate of change of fingertip temperature has also been shown to be correlated to sympathetic nervous system state (Kistler et al., 1998); consequently, the centroid of the slope of the unfiltered temperature signal was calculated for each second of the recorded data. **Respiration:** Respiration has been successfully characterized in fields such as polygraphy by a measure called the respiration length line (RLL), a combined measure of respiration rate and amplitude (Ben-Shakhar & Dolev, 1996). It is produced by summing the distance between successive points of the respiration signal within a five second window. To ensure that this measure is not disproportionately affected by the starting point of the measurement on the curvilinear respiration pattern, the average is calculated across ten measures of RLL, each beginning 0.1 seconds after the previous calculation, yielding the feature $RLL_{avg}(t)$. The interested reader is referred to (Blain, Power et al., 2010) for more details. **Blood volume pulse:** Blood volume pulse is also often characterized by rate and amplitude; consequently, we use the same procedure detailed for respiration above, yielding a measure of $BLL_{avg}(t)$. By definition, $BLL_{avg}(t) > 0$ and $RLL_{avg}(t) > 0$, consequently, the distribution of both variables is positively skewed; to mitigate this effect, the logarithm of both variables is calculated, yielding the final features $logRLL(t)$ and $logBLL(t)$. For notational convenience, each feature extracted from the raw physiological signals is herein referred to as $f(*)$, where the * denotes the physiological signal it was derived from. The features derived from the raw signals presented in Figure 7-1 are illustrated in Figure 7-2.
Figure 7-2 Features extracted from the raw physiological signals presented in Figure 1. Features are represented as f(*), where * denotes the source of the original physiological signal.

7.3.1.3 Classification

Step 1: Embedding

Let $x_{1j}, x_{2j}, \ldots, x_{Mj}$ be the $j^{th}$ time series ($j = 1, \ldots, 4$ in the present case) and $M$ be the number of data points in the series. Define the baseline matrix:

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ \vdots & \vdots & \vdots & \vdots \\ x_{M1} & \cdots & \cdots & x_{M4} \end{bmatrix}$$  \hspace{1cm} (1)$$

Thus, $X$ represents multivariate data with 4 characteristics and $M$ observations for each characteristic. Subsequently, define the test matrix:

$$U = \begin{bmatrix} u_{11} & u_{12} & u_{13} & u_{14} \\ u_{21} & u_{22} & u_{23} & u_{24} \\ \vdots & \vdots & \vdots & \vdots \\ u_{K1} & \cdots & \cdots & u_{K4} \end{bmatrix}$$  \hspace{1cm} (2)$$
where K is the number of data points in the series. In both X and U matrices, the columns represent the signal features extracted from BVP, EDA, skin temperature and respiration, respectively.

Using the mean vector $\mu_X = [E(x_1)\ E(x_2)\ E(x_3)\ E(x_4)]^T$, where $x_j$ is the $j^{th}$ column of X, calculate the 4x4 covariance matrix of X.

$$\Sigma = E[(x - \mu_x)(x - \mu_x)^T]$$  \hfill (3)

Cholesky decomposition of $\Sigma$ provides us with lower triangular matrix $L$ with strictly positive diagonal entries.

$$\Sigma = LL^T$$  \hfill (4)

**Step 2: Construction of a 4-Dimensional Baseline Hypersphere**

Define a matrix $\Upsilon$ such that $\text{var}(\Upsilon_j) = 1$ for $j = \{1,...,4\}$.

$$\Upsilon = (X - \mu_x)L^{-1}$$  \hfill (5)

The columns of $\Upsilon$ represent the same physiological signals of the columns of X, and, being orthogonal, define a 4-dimensional vector space, which we call the baseline space. We now create a hypersphere that encapsulates 95% of the elements in $\Upsilon$, recognizing that there may be some outliers within the baseline resting state. As such, we choose the radius of this hypersphere to be the minimum $r \in \mathbb{R}^+$, such that:

$$\sum_{m=1}^{M} P(r^2 \geq \sum_{j=1}^{4} (\Upsilon_{mj} - E[\Upsilon_j])^2) \geq 0.95$$  \hfill (6)

We will consider all points in $\mathbb{R}^4$ that fall within the space enclosed by radius $r$ to be generated by a resting physiological state.
**Step 3: Projection of Test Data into Baseline Space**

To project data collected in the intervention period into its corresponding baseline space, transform the elements of test matrix $R$ into the baseline space, creating a $K \times 4$ matrix $S$ using the variables defined in equation (5).

$$S = (U - \bar{\mu}_U)L^{-1}$$  \hspace{1cm} (7)

In matrix $S$, each column represents a transformed feature of one physiological signal, and thus, each row is a four dimensional vector or point in $\mathbb{R}^4$ that represents the states of the physiological signals for one second of data collected during the intervention period.

**The Decision Rule**

Define a binary label $D_k, 1 \leq k \leq K$, to denote the membership of the $k^{th}$ row of $S$ in the baseline space. Namely, $D_k = 0$ indicates that the $k^{th}$ row is considered within the baseline space. The label is defined by the following decision rule:

$$D_k = \begin{cases} 
0 & \text{if } \sum_{j=1}^{4} (s_{kj} - E[Y_j])^2 \leq r^2 \\
1 & \text{otherwise}
\end{cases}$$ \hspace{1cm} (8)

Let $I$ represent the total number of outliers, i.e., points in the test set $S$ that fall outside a 95% confidence hypersphere of radius $r$, where:

$$I = \sum_k D_k \quad \text{for } 1 \leq k \leq K$$ \hspace{1cm} (9)

The magnitude of $I$ within a given time period is representative of the amount of time the individual was in a non-resting physiological state, hence, the intensity of their reaction to the stimulus.

Steps 1 to 3 are represented in Figure 7-3.
Figure 7-3 a) Raw physiological data b) Transformed physiological data c) Outlier with respect to baseline hypersphere. Note: only 3 variables are shown to facilitate visualization.
**Step 4: Characterization of Outliers**

In order to characterize the contribution of each physiological signal to each outlier, we transform each outlier back to the original space.

First, we construct matrix $O$ containing all the outliers in the test set. For $1 \leq k \leq K$:

If $D_k = 1$, $O_k = \left[ \frac{O_{k-1}}{S_k} \right]$, where $S_k$ is the $k^{th}$ row of $S$ and $O_0 = \{0\}$ initially.

The notation $[O_{k-1}/S_k]$ denotes a stacking of the row $S_k$ onto $O_{k-1}$. Subsequently, we construct matrix $P$ of size $[I \times 4]$ by transforming the elements in $O_K$ back into the original space, such that the axes are representative of the units of their respective physiological measures.

$$P = O_k L^{-1} + \bar{\mu}$$

(10)

Each row in $P$ is a four dimensional vector, or a point in $\mathbb{R}^4$, that represents the state of the physiological signals that do not belong in a baseline resting state. The relative contribution of each column (i.e., each physiological signal) in $P$ is representative of the pattern of physiological signal changes an individual experiences in reacting to a given stimulus.

In summary, for each data recording session, the algorithm yields two measures: $I$, which characterizes the intensity of the change in physiological state, and $P$, which represents the patterns of the physiological signals responsible for the state change.

**7.3.2 Comparing Physiological Responses Between Interventions**

In Lang’s two-dimensional theory of emotion, emotions can be accurately discriminated along the axes of arousal and valence (Lang, 1998). The algorithm presented in this paper applies Lang’s theory to physiological changes mediated by the autonomic system and develops a corresponding two-dimensional measure of physiological state. The intensity of change to a given stimulus ($I$) along one axis parallels Lang’s measure of arousal, and the pattern of change to a given stimulus ($P$) along the next axis parallels Lang’s measure of valence. Using Lang’s system, it is possible to compare and contrast an individual’s emotional reaction to two different affective stimuli. In the subsequent section, a method by which the proposed algorithm can be
used similarly to compare and contrast an individual’s physiological reaction to two different affective stimuli is presented.

Assume an ABAB study design wherein participants are exposed to two different affective stimuli after an initial baseline period. Processing the four autonomic signals of interest with equations (1) to (10) of the proposed algorithm yields four measures of the intensity of the response: $I^{A_1}$, $I^{A_2}$, $I^{B_1}$ and $I^{B_2}$, and four corresponding matrices representing patterns of response: $P^{A_1}$, $P^{A_2}$, $P^{B_1}$ and $P^{B_2}$. Theoretically, an individual’s differential physiological reaction to affective stimuli $A$ and $B$ could manifest as either differences in intensity of response, patterns of response, or a combination of both.

First, we compare intensity of the individual’s reaction between interventions to determine whether or not there is consistency in their response. In particular, the participant demonstrates consistency in their intensity of response and is classified as an intensity responder if:

$$\min(I^{A_1}, I^{A_2}) > \max(I^{B_1}, I^{B_2}) \quad \text{or} \quad \min(I^{B_1}, I^{B_2}) > \max(I^{A_1}, I^{A_2})$$

Next, we proceed to determine whether or not patterns of physiological signals demonstrate consistency of response between interventions. Specifically, the participant demonstrates consistency in their pattern of response in the corresponding physiological signal if:

$$\min(P^{A_1}_{\mu}, P^{A_2}_{\mu}) > \max(P^{B_1}_{\mu}, P^{B_2}_{\mu}) \quad \text{or} \quad \min(P^{B_1}_{\mu}, P^{B_2}_{\mu}) > \max(P^{A_1}_{\mu}, P^{A_2}_{\mu})$$

where $P^{A_{i,j}}_{\mu}$ is the average of the $j^{th}$ column, $j = 1,...,4$, of $P^{A_i}$, the pattern of reaction matrix for treatment $A_i$. The other average quantities are defined the same way. Consistency of response in at least one physiological signal classifies the individual as a pattern responder. The procedure outlined in this section can be used to compare physiological responses between interventions in studies designed for as few as two repetitions of each intervention (i.e., ABAB); studies with greater than two repetitions of each intervention allow statistical comparison of intensity and pattern between conditions to be made.
In this manner, an individual’s physiological reaction to two different conditions can be quantified along an intensity versus pattern axis, and changes in physiological state can be quantified and compared to each other.

### 7.3.3 Application

We illustrate the merits and limitations of this algorithm by applying it to the autonomic physiological signals of children in a long-term rehabilitation hospital. The data presented herein is part of a larger study investigating the effect of therapeutic clowns on inpatients in a long-term health care setting; the interested reader is referred to (Blain, Kingsnorth, & McKeever, 2010) for more details. Eight inpatients (4 male, mean age 10.7 ± 5 years) with primary diagnoses that included arterio-venous malformation, Guillan-Barré syndrome, macrophage activation syndrome, transverse myelitis, cerebral palsy and encephalopathy participated in this study. Five of the participants were verbally and behaviourally expressive. Physiological signals were gathered while the children were exposed to two affective conditions: watching television and interacting with Therapeutic Clowns. The four peripheral autonomic physiological signals of interest were monitored using non-invasive sensors from Thought Technology: (1) EDA, monitored using two gel-less Ag/Ag-Cl electrodes attached to the medial phalanges of the second and third fingers of the participant’s non-dominant hand; (2) skin temperature, using a surface thermistor attached to the fifth finger of the same hand; (3) blood volume pulse (BVP), using an infrared sensor attached to the fourth finger of the same hand, and; (4) respiration, using a piezoelectric belt secured around the participant’s thoracic cavity. All sensors were sampled at a frequency of 256 Hz.

Participants were exposed to two conditions over the course of 4 days in an ABAB study design. In Condition A, participants were instructed to relax in a comfortable position for 5 minutes, and then watch a television program of their choice for 10 minutes. In Condition B, participants were again instructed to relax in a comfortable position for 5 minutes, and then were requested to minimize their movement as they were given the opportunity to interact for 10 minutes with two Therapeutic Clowns that regularly visit the rehabilitation facility. The algorithm was applied to data gathered from all 4 days using $M = 300$ in equation (1) and $K = 600$ in equation (2). Intensity ($I$) and pattern ($P$) results were compared between conditions to determine their effect.
7.4 Results

For each of the eight participants, the intensity of reaction \((I)\) and the pattern of reaction \((P)\) are presented in Tables 7-1 and 7-2, respectively. Participants that demonstrated differential reaction to the two conditions (Table 7-1 and 7-2) and the physiological signals within each participant where these responses (Table 7-2) manifested are denoted with an asterix. Missing information due to data collection error is denoted n/a; for sessions when this occurred, the corresponding measures of intensity and pattern were omitted as inputs to equations (11 and 12).

**Table 7-1** Intensity of Reaction, \(I\)

<table>
<thead>
<tr>
<th>Participant</th>
<th>Condition</th>
<th>A1</th>
<th>B1</th>
<th>A2</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td></td>
<td>46</td>
<td>n/a</td>
<td>28</td>
<td>124</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>145</td>
<td>n/a</td>
<td>38</td>
<td>406</td>
</tr>
<tr>
<td>3*</td>
<td></td>
<td>12</td>
<td>523</td>
<td>22</td>
<td>134</td>
</tr>
<tr>
<td>4*</td>
<td></td>
<td>25</td>
<td>454</td>
<td>243</td>
<td>479</td>
</tr>
<tr>
<td>5*</td>
<td></td>
<td>46</td>
<td>85</td>
<td>8</td>
<td>119</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>244</td>
<td>165</td>
<td>92</td>
<td>78</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>220</td>
<td>168</td>
<td>299</td>
<td>n/a</td>
</tr>
<tr>
<td>8*</td>
<td></td>
<td>10</td>
<td>523</td>
<td>n/a</td>
<td>339</td>
</tr>
</tbody>
</table>

7.5 Discussion

Each participant who was able to verbally self-report their emotional state indicated little to no change in valence in response to watching television, and a large positive change in valence in response to interacting with the Therapeutic Clowns. These verbal reports support the results observed in Tables 7-1 and 7-2 – every individual demonstrated a consistent difference in either the intensity or pattern of their physiological state between watching television and interacting with the clowns. Interestingly, these differential changes in either the intensity or pattern of physiological state are observed in participants 3, 5 and 8, all of whom had disabilities that rendered them unable to move or speak. Unable to verbally express their affective perception of the presented stimuli, and with no behavioural indicators of preference or reaction, these children are often assumed to be unaware of their situation and environment. The results of this algorithm may suggest that despite a lack of physical evidence, these children are indeed differentially responsive to their environment, as each of them responded consistently and differentially to the two presented stimuli. This algorithm may be useful for detecting changes in physiological state that could be correlated to their intentions and preferences.
Table 7-2 Pattern of Response, $P$

<table>
<thead>
<tr>
<th>Participant</th>
<th>Signal</th>
<th>Condition A1</th>
<th>Condition B1</th>
<th>Condition A2</th>
<th>Condition B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>BVP*</td>
<td>0.023</td>
<td>n/a</td>
<td>0.011</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>EDA</td>
<td>-0.01</td>
<td>n/a</td>
<td>-0.003</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>Temp*</td>
<td>-0.019</td>
<td>n/a</td>
<td>-0.014</td>
<td>0.638</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
<td>-0.009</td>
<td>n/a</td>
<td>-1.576</td>
<td>-1.235</td>
</tr>
<tr>
<td>2*</td>
<td>BVP</td>
<td>0.001</td>
<td>n/a</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>EDA</td>
<td>-0.002</td>
<td>n/a</td>
<td>0.013</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>Temp*</td>
<td>-0.008</td>
<td>n/a</td>
<td>-0.175</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
<td>1.348</td>
<td>n/a</td>
<td>-0.483</td>
<td>-0.188</td>
</tr>
<tr>
<td>3*</td>
<td>BVP*</td>
<td>0.0001</td>
<td>-0.0001</td>
<td>0.0008</td>
<td>-0.0002</td>
</tr>
<tr>
<td></td>
<td>EDA</td>
<td>0</td>
<td>-0.0002</td>
<td>-0.0001</td>
<td>-0.0003</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
<td>-0.068</td>
<td>0.182</td>
<td>0.430</td>
<td>-0.378</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
<td>0.254</td>
<td>-0.286</td>
<td>-0.097</td>
<td>-0.496</td>
</tr>
<tr>
<td>4</td>
<td>BVP</td>
<td>0.003</td>
<td>0.010</td>
<td>0.037</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>EDA</td>
<td>0.014</td>
<td>-0.0003</td>
<td>-0.002</td>
<td>-0.0006</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
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<td>0.200</td>
<td>0.180</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
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<td>0.236</td>
<td>-0.478</td>
<td>-0.768</td>
</tr>
<tr>
<td>5*</td>
<td>BVP</td>
<td>0.129</td>
<td>0.023</td>
<td>0.020</td>
<td>0.147</td>
</tr>
<tr>
<td></td>
<td>EDA</td>
<td>-0.001</td>
<td>-0.002</td>
<td>-0.001</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>Temp*</td>
<td>0.130</td>
<td>0.074</td>
<td>0.182</td>
<td>-0.258</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
<td>-0.073</td>
<td>-0.405</td>
<td>-0.092</td>
<td>-0.177</td>
</tr>
<tr>
<td>6*</td>
<td>BVP</td>
<td>-0.004</td>
<td>0.002</td>
<td>0.029</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>EDA</td>
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<td>-0.01</td>
<td>-0.001</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td>Temp*</td>
<td>-0.159</td>
<td>0.354</td>
<td>-0.279</td>
<td>0.628</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
<td>-0.142</td>
<td>1.84</td>
<td>-1.22</td>
<td>-0.553</td>
</tr>
<tr>
<td>7</td>
<td>BVP</td>
<td>0.001</td>
<td>0.003</td>
<td>0.003</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>EDA*</td>
<td>-0.002</td>
<td>0.0001</td>
<td>-0.008</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Temp*</td>
<td>0.006</td>
<td>0.164</td>
<td>0.091</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
<td>-0.543</td>
<td>0.548</td>
<td>-0.125</td>
<td>n/a</td>
</tr>
<tr>
<td>8*</td>
<td>BVP*</td>
<td>-0.004</td>
<td>0.001</td>
<td>N/A</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>EDA</td>
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<td>-0.001</td>
<td>n/a</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
<td>0.039</td>
<td>0.014</td>
<td>n/a</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Resp</td>
<td>0.169</td>
<td>-0.177</td>
<td>n/a</td>
<td>0.910</td>
</tr>
</tbody>
</table>

7.5.1 Strengths and Limitations of the Algorithm

Physiological signals demonstrate such profound inter- and intra-subject variability that it is only with great difficulty that changes in physiological state can be compared between and within individuals. This large variation in baseline physiological state is even more pronounced in individuals that have conditions that intrinsically affect their autonomic nervous system, such as children with severe disabilities. The potential degree of intra-subject variability is illustrated in Figure 7-4a, which depicts the baseline state of three physiological signals from participant 3 over two separate days; there is no overlap in the baseline clusters in spite of the fact that the
participant is at rest on both occasions, and patterns of physiological signals that constitute a significant change on one day belong to resting state on the next.

The proposed algorithm addresses this challenge by re-establishing an individual’s baseline physiological state on a day-to-day, recording-to-recording basis. As such, observed physiological changes such as an increase in skin temperature are only considered significant if they fall outside the boundaries defined by the session-specific baseline space. While allowing comparison between individuals, this algorithm’s strength lies in its use of an individual as his or her own control. Figure 7-4b illustrates the differential responding of two different participants to the two stimuli; while participant 6 exhibits significant temperature decrease in response to watching television and significant temperature increase in response to interacting with the Therapeutic Clowns, the opposite behaviour is observed in participant 5. Instead of comparing physiological state changes to an average behaviour with the potential of losing individual idiosyncratic patterns, this algorithm takes into account each individual’s unique pattern of physiological response.

This algorithm also expands existing univariate models of physiological state change to a multivariate algorithm that accounts for the systemic effect of stimulation to the autonomic system. Individual responses to autonomic stimulation manifest in patterns particular to the individual (J. I. Lacey & Lacey, 1958). This algorithm does not make any assumptions about the individual’s primary modality of response, and enables physiological state change to be tracked whether it is manifested in one individual physiological signal, or a combination of such signals.
While this algorithm provides quantitative measures of physiological state change that align with Lang’s popular theory of emotional state change, it is limited in its ability for its output to be verified. As outlined, there does not exist a gold standard for detecting systemic physiological state change, and the current measures of self-report are subjective and unreliable for comparison between individuals. Consequently, the sensitivity and accuracy of this algorithm cannot be determined. Further experiments must be conducted to validate these changes against self expression and behavioural data. In addition, while this algorithm can easily be expanded to encompass more than four physiological signals, caution must be exercised to ensure that the baseline recording is long enough to address the corresponding increase in dimensionality.
7.6 Conclusion

Changes in the physiological state of an individual are difficult to compare both between and within individuals due to the lack of a means to objectively quantify these changes. This paper presents an algorithm that addresses both the multivariate nature of physiological state, and the profound inter- and intra-subject variability of these signals. By establishing a baseline four-dimensional feature space against which signals collected during exposure to a given condition can be compared, the algorithm yields measures of the intensity and the pattern of the individual’s physiological reaction. These measures are in keeping with arousal and valence measures developed by Lang to quantify changes in emotional state. Further work needs to be done to validate the model, and to determine its use with other combinations of physiological signals.

7.7 Acknowledgements

This work was supported by a Bloorview Research Institute Seed Grant [#08-054]
8 Theme 2 Variation 3: The Auditory Environment

A Cardiorespiratory Classifier of Voluntary and Involuntary Electrodermal Activity

The preceding variations have addressed the effect of the built and social environments on individuals with profound disabilities. This variation addresses the effect of the auditory environment on an individual’s physiological signals by answering the questions: 1) What are the physiological effects of startling noises? and, 2) Can a physiological-signal based filter be developed that differentiates patterns of peripheral autonomic nervous system signals due to voluntary effort from reaction to environmental sounds? This variation demonstrates that physiological signals are differentially affected by the auditory environment in comparison to mental state. The presented algorithm uses this effect to filter out the effects of environmental sounds on physiological signals, addressing a challenge of this channel of person-environment interaction presented in Theme 1 variation 1, and enabling more robust physiologically-mediated interactions between the person and the environment to occur.

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8.1 Abstract

**Background:** Electrodermal reactions (EDRs) can be attributed to many origins, including spontaneous fluctuations of electrodermal activity (EDA) and stimuli such as deep inspirations, voluntary mental activity and startling events. In fields that use EDA as a measure of psychophysiological state, the fact that EDRs may be elicited from many different stimuli is often ignored. This study attempts to classify observed EDRs as voluntary (i.e., generated from intentional respiratory or mental activity) or involuntary (i.e., generated from startling events or spontaneous electrodermal fluctuations). **Methods:** Eight able-bodied participants were subjected to conditions that would cause a change in EDA: music imagery, startling noises, and deep inspirations. A user-centered cardiorespiratory classifier consisting of 1) an EDR detector, 2) a respiratory filter and 3) a cardiorespiratory filter was developed to automatically detect a participant’s EDRs and to classify the origin of their stimulation as voluntary or involuntary. **Results:** Detected EDRs were classified with a positive predictive value of 78%, a negative predictive value of 81% and an overall accuracy of 78%. Without the classifier, EDRs could only be correctly attributed as voluntary or involuntary with an accuracy of 50%. **Conclusions:** The proposed classifier may enable investigators to form more accurate interpretations of electrodermal activity as a measure of an individual’s psychophysiological state.

8.2 Background

Electrodermal activity (EDA) is one of the most popular methods of measuring arousal, attention and orientation in fields such as psychology (Bauer, 1998), emotion recognition (Picard et al., 2001) and psychophysiology (Ben-Shakhar & Dolev, 1996). It consists of a slowly evolving baseline and quick, transient changes known as electrodermal reactions (EDRs), defined as increases in EDA of over 0.05 µS within five seconds (Boucsein, 1992). EDRs are a result of cholinergic stimulation of the sweat glands, causing increases in electrical conductance of the skin. These fluctuations in conductivity are interpreted as a measure of overall arousal of the sympathetic nervous system. While amplitude, latency and fall time are routinely reported, reporting the stimulus of an EDR remains challenging. In particular, it is difficult to discern among uncued increases in EDA due to: (1) spontaneous increase, often referred to as a non-specific EDR; (2) result of internal stimulation (e.g. mental stimulation, a large amplitude inspiration, biting the tongue); or (3) result of external stimulation (e.g. startling noises, changes
in visual stimulation) (Ben-Shakhar & Dolev, 1996; Hay, Taylor, & Nukada, 1997; Malmivuo & Plonsey, 1995; Rittweger, Lambertz, & Langhorst, 1997; Weisz & Czigler, 2006).

Often, it is important to be able to attribute an EDR to one of the three aforementioned sources. For example; in the field of polygraphy, EDA is often measured as suspects are administered a series of questions, one of which pertains to knowledge of the details of the crime (i.e. the Guilty Knowledge Test or the Concealed Information Test). An EDR succeeding a crime-relevant question indicates that the suspect is lying, and can be used to detect 94.2% of innocent suspects and 83.9% of guilty suspects, under controlled conditions (Ben-Shakhar & Furedy, 1990). However, EDRs can be voluntarily generated using a variety of physical and mental activities, significantly decreasing the accuracy of the test. Clearly, having a method of distinguishing the involuntary guilty reaction from the voluntary mental activities would significantly enhance the reliability of polygraphy examinations. Differentiation between voluntary and involuntary electrodermal activity may also be useful in the field of access pathways for individuals with severe and multiple disabilities. Numerous options have been explored to enable individuals without speech or reliable motor movement to interact with the environment, among them, the use of electrodermal activity as an access pathway (Blain, Mihailidis et al., 2008; Tai et al., 2008).

While voluntarily generating EDRs to indicate intent remains a promising access pathway for these individuals, the use of this signal for precise and reliable communication has been contested on the grounds of high incidences of metabolic noise (Kubler et al., 2001); the ability to distinguish involuntary EDRs from voluntary ones would greatly enhance the robustness of this access pathway.

Despite enormous advancements in the procedures and equipment involved in recording electrodermal activity, Landis’s (Landis, 1930) comments eighty years ago on the inability to attribute psychological significance to a single EDR are still applicable today. He provides an extensive list of EDR sources, illustrating the magnitude of the challenge of determining the origin of a single observed EDR. To address this challenge, many studies have been conducted in a controlled environment, enabling the assumption that all observed EDRs are a result of varying the stimulus of interest (Armel & Ramachandra, 2003; Hay et al., 1997; Khalfa et al., 2002; Venables & Mitchell, 1996). The validity of this assumption is often not discussed; in addition, many studies occur in environments that are not controlled. In these situations, Cacioppo and Tassinary (Cacioppo & Tassinary, 1990) have suggested that in order to develop
clear psychophysiological inferences of one signal, it is necessary to consider other physiological signals that may vary with the psychological event of interest. Studies that have examined patterns of physiological signals have clearly established that respiratory and cardiac artefacts also vary with many of the aforementioned EDR sources (B. C. Lacey & Lacey, 1980; Seto-Poon et al., 2005). To date, numerous EDA studies have followed Cacioppo and Tassinary’s suggestion, taking respiratory and cardiac signals into consideration in one of three ways:

1) Cardiac and respiratory signals are recorded simultaneously with electrodermal activity. However, all signals are analyzed independently, not taking into account the interaction among the signals (Bauer, 1998; Elaad & Ben-Shakhar, 1991; Turpin et al., 1999; Weisz & Czigler, 2006).

2) The interaction among cardiac, respiratory and EDA signals is acknowledged. However, procedures for removing cardiac and respiratory artefacts are not described (Godert et al., 2001; Nater, Abbruzzese, Krebs, & Ehlert, 2006; Vetrugno et al., 2003).

3) Cardiac, respiratory and EDA signals are recorded simultaneously. Features from each signal are extracted independently and used as independent inputs into a classifier that determines the overall source of all the EDRs recorded within the classification period (Ben-Shakhar & Dolev, 1996; Cacioppo & Tassinary, 1990; Ekman et al., 1983; Elaad, 1990; Elaad & Ben-Shakhar, 2006; Katsis et al., 2006; Kettunen, Ravaja, Naatanen, Keskivaara, & Keltikangas-Jarvinen, 1998; Picard et al., 2001; Rousmans, Robin, Dittmar, & Vernet-Maury, 2000).

The first two methods do not sufficiently account for the interaction between these physiological signals. The third method follows in the spirit of Cacioppo and Tassinary, improving classification accuracy by accounting for the changes in more than one physiological signal. However, while this third method is useful for classifying an individual’s psychophysiological state based on a long term recording, it is unable to determine the source of a single EDR, a process necessary for the real-time application of polygraphy and access mentioned earlier. To date, few efforts have been made towards single EDR discrimination; Crone et. al (Crone, Somsen, Van Beek, & Van Der Molen, 2004) used the respiratory signal to eliminate heart rate and skin conductance changes associated with gross respiratory manoeuvres, and Schneider et. al
(Schneider, Schmidt, Binder, Schafer, & Walach, 2003) have developed a set of rule-based guidelines to eliminate respiration-related artefacts in EDA recordings.

While the aforementioned techniques exist to eliminate respiratory-related artifacts from the EDA signal, they typically involve manual, offline analysis of the respiratory signal, and are unsuited for real-time EDR classification. Additionally, there currently exists no means of distinguishing voluntarily generated EDRs from involuntary EDRs using respiratory information alone. The purpose of this study is to develop a classifier that uses information from non-EDA physiological signals, namely, respiration and heart rate, to classify the source of a single EDR into one of two categories: (1) a voluntarily generated EDR, including those generated by internal physiological processes such as inspiration and internal mental processes such as music imagery; and (2) an involuntary EDR, including those generated by external startling stimuli and non-specific EDRs.

8.3 Methods

8.3.1 Participants

A convenience sample of eight able-bodied individuals (3 males, mean age 26 ± 3 years) participated in this study. Participants did not have conditions that may have affected their physiological signals and/or their ability to perform the required tasks, including metabolic, cardiovascular, respiratory, psychiatric, or drug- or alcohol-related disorders. Participants also had normal, or corrected to normal, hearing, were electrodermally labile and had a periodic baseline respiration pattern. Ethical approval was received from the relevant institutions and all participants provided written consent.

8.3.2 Instrumentation

Three peripheral physiological signals were recorded from each subject using the ProComp Infiniti data acquisition system (Thought Technology). These were: (1) electrodermal activity, using two Ag/Ag-Cl gel-less electrodes attached to the medial phalange of the second and third fingers; (2) respiration, using a piezoelectric belt positioned around the subject’s thoracic cavity; and (3) blood volume pulse, measured using an infrared sensor attached to the subject’s fourth finger. All sensors were placed on the subject’s non-dominant hand, and sampled at a frequency of 256 Hz. No additional filters or amplifiers other than those intrinsic to the ProComp Infiniti
hardware were employed. Subjects were blindfolded and asked to don a pair of soundproof ear covers over a set of headphones, to ensure that the external stimuli being presented to each subject were fully controlled by the experimenter. Typical signals that were recorded from all sensors are presented in Figure 8-1.

![Typical signals recorded from the EDR sensors.](image)

**Figure 8-1** Typical signals recorded from the EDR sensors. Raw electrodermal activity, respiration and heart rate signals recorded from the ProComp Infiniti hardware.

### 8.3.3 Protocol

Participants were seated comfortably in front of a computer as the sensors were attached. Prior to the data collection, participants were asked to choose several songs of their own preference and of the same valence (i.e. happy or sad), which they felt elicited a strong emotional reaction. The participants were informed that when cued in the experiment, they would be required to perform music imagery of one of their chosen songs, in other words, to sing the song vividly in their head. They were additionally informed that the purpose of the imagery was to elicit an emotional reaction, thus, when they began to feel emotionally habituated to their current song, they were requested to switch to another song. Visual inspection of the recorded physiological signals confirmed that music elicited sympathetic excitation in all participants. After choosing
their songs, the participants performed the four sets of trials outlined in Table 8-1. The order of the trial presentation was randomized for each participant, and the participants performed the activities over two separate days to ensure maximum concentration and focus during each trial.

**Table 8-1** Summary of Experimental Trials

<table>
<thead>
<tr>
<th>Trial Block</th>
<th>Trial Description</th>
<th>Total Time</th>
<th>Time of Presentation of Startles (s)</th>
<th>Trials without noise</th>
<th>Trials with noise</th>
<th>Total trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Quiet resting</td>
<td>2 min, 10 s</td>
<td>N/A</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>Music imagery</td>
<td>3 min, 40 s</td>
<td>N/A</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>Quiet resting with startles</td>
<td>2 min, s</td>
<td>20, 45, 65, 90, 110</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>Music imagery with startles</td>
<td>3 min, 46 s</td>
<td>1, 31, 59, 111, 149, 191</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

In Block A trials (quiet resting trials), subjects were instructed to relax and clear their minds of thought, keeping their bodies as still as possible. During Block B trials (music imagery), the investigators cued subjects every 20 seconds via a gentle tap on their arm to alternate between quiet resting and performing music imagery. For Block C trials (quiet resting with startles), participants received the same set of instructions as in Block A. At the time points indicated in Table 8-1, participants were presented with one of five auditory startling stimuli through their headphones. Characteristics of these stimuli are presented in Table 8-2. During Block D trials (music imagery with startles), participants received the same instructions as Block B trials, and one of the five auditory stimuli in Table 8-2 were presented at the time points indicated in Table 8-1. Prior to Block A and B trials, participants were asked to take 3 deep breaths over the course of 1 minute so as to elicit inspiratory-induced EDRs. Trials in all four blocks were conducted under two conditions: (1) in silence, and (2) in the presence of a continuous background noise (an air conditioner), yielding a total of 16 recorded trials. The presence of background noise has been noted to enhance startle reactivity in humans (Flaten, Nordmark, & Elden, 2005); this condition was included to develop a classifier trained on EDRs generated in both controlled and naturalistic environments.
**8.3.4 Proposed Cardiorespiratory Classifier**

The following section will present the three elements that constitute the proposed cardiorespiratory classifier of electrodermal activity (Figure 8-2).

---

**Table 8-2** Auditory startle sound characteristics

<table>
<thead>
<tr>
<th>Sound</th>
<th>Intensity (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dog bark</td>
<td>60 ± 2</td>
</tr>
<tr>
<td>Glass shattering</td>
<td>91 ± 2</td>
</tr>
<tr>
<td>Door slam</td>
<td>69 ± 3</td>
</tr>
<tr>
<td>Cough</td>
<td>79 ± 1</td>
</tr>
<tr>
<td>Sneez</td>
<td>82 ± 1</td>
</tr>
</tbody>
</table>

---

**Figure 8-2** Overview of the cardiorespiratory classifier. Electrodermal reactions are identified from the raw EDA signal by the automatic EDR detector. These EDRs are subsequently tested by the respiratory and cardiorespiratory filters to determine whether they were voluntarily or involuntarily generated by the participant.
8.3.4.1 Automatic EDR detection

To detect EDRs, we employed the rule-based classifier proposed by Blain et al. (Blain, Mihailidis et al., 2008). Here, we only review the main concepts of the method and refer the reader to the original article for additional details. The gradient of baseline electrodermal activity is predominantly negative; during the initiation of an electrodermal reaction, this gradient becomes sharply positive. As a result, the first difference of the EDA signal is a discriminatory feature that indicates the presence of electrodermal reactions. In particular, the mean (C) of the distribution of the first difference of the EDA signal over a one second window can be used to detect the presence of an EDR (Blain, Mihailidis et al., 2008); this process is summarized in Figure 8-3.

Figure 8-3  Automatic EDR detection algorithm. The mean of the histogram of the derivative of the EDA signal (C) is compared to the threshold (D) to determine whether a one second interval of EDA contains an EDR (Blain, Mihailidis et al., 2008).
The threshold (D), as referred to in Figure 8-3, must be determined for each individual experimental protocol, and is defined such that:

If $C < D$, the EDA signal from $(t_i, t_i + 1)$ contains no EDRs.

If $C \geq D$, the EDA signal from $(t_i, t_i + 1)$ is part of an EDR.

D was chosen via an receiver operating characteristic analysis to simultaneously maximize sensitivity and specificity of EDR detection. To this end, a typical EDA signal was selected at random from a Block A trial of one of the participants. In this signal, five EDRs of varying amplitudes were identified manually. A maximum sensitivity and specificity of 100% were achieved at a value of $D = 4 \times 10^{-4}$. Using this threshold, a sensitivity and specificity of 100% were achieved for all trials of each of the eight subjects. This method of identifying EDRs is similar in principle to other methods that use first derivatives to define the start point, peak and end point of an observed EDR, but is more general in its abilities (Frantzidis, Konstantinidis, Pappas, & Bamidis, 2009). While it has the same ability to identify EDRs as the algorithm proposed by Frantzidis et al., this method does not have the ability to define the characteristics of the response.

8.3.4.2 Respiration Filter

Having presented a method to detect EDRs, we now introduce a respiratory filter whose purpose is to remove respiration-induced EDRs. Deep inspirations are known sympathetic stimuli – subjects are often asked to take a deep breath while EDA equipment is being set up and calibrated, as it is an established method of generating an EDR (Hay et al., 1997; Seto-Poon et al., 2005). The characteristics of the respiration signal as recorded via a piezoelectric belt have a large variance not only between subjects, but within subjects as well. In addition to natural circadian variations of respiratory patterns, the position and tension of the belt is not identical between trials, resulting in a large intrasubject variability. As a result, specific features cannot be used to classify a deep inspiration from typical respiration patterns. Instead, we propose to detect the point at which respiration patterns deviate significantly from a baseline respiration model developed for each session, for each participant. Details of our algorithm follow below.

The algorithm uses the respiration length line (RLL) to characterize each second of the respiration signal. RLL combines the measures of respiration rate and amplitude, and is a
common measure of respiration suppression (Ben-Shakhar & Dolev, 1996). A decreased respiration rate and a decrease in respiration amplitude result in a shorter length line. Let the respiration signal generated by the expansion and contraction of the lung cavity be represented by \( r(t) \) and the sampling frequency of the signal be represented by \( f \) (in this protocol, \( f = 256 \) Hz). The respiration length line is produced by summing the Euclidean distance between successive points within a five second window of \( r(t) \), as presented in equation (1).

\[
RLL(t) = \int_{0}^{5} \sqrt{[r(t + s + \delta) - r(t + s)]^2 + \delta^2} \, ds \quad \text{where} \quad \delta = \frac{1}{f}
\]

This single measure of RLL is disproportionately affected by the starting point of measurement on the curvilinear respiration pattern. Following the solution outlined by Ben-Shakhar et al. (Ben-Shakhar & Dolev, 1996) we address this problem by recalculating the RLL within a five second window 10 more times, each time beginning the measurement 0.1 seconds after the previous calculation. The average of these 10 measurements yields \( RLL_{\text{avg}}(t) \) for each second of the recorded signal, as illustrated in equation (2).

\[
RLL_{\text{avg}}(t) = \frac{1}{10} \sum_{i=0}^{9} RLL(t - 0.1i)
\]

The 5% trimmed mean (\( \mu_{\text{trim}} \)) and trimmed standard deviation (\( \sigma_{\text{trim}} \)) for the resultant \( RLL_{\text{avg}}(t) \) signal are then calculated for the baseline signals, yielding robust measures of the distribution of respiration length lines during quiet breathing (Rand, 1997). We define the respiratory threshold \( \psi \) as \( \psi = \mu_{\text{trim}} \pm 3 * \sigma_{\text{trim}} \). For the remainder of the trials, each \( RLL_{\text{avg}}(t) \) is compared against this respiratory threshold, such that if \( | RLL_{\text{avg}}(t) | > \psi \), the respiration signal contained in the 5 second window beginning at time \( t \) contains an irregular breath, i.e., one that departs from baseline respiration.

8.3.4.3 The Bootstrap Variability Cardiorespiratory Classifier

8.3.4.3.1 Cardiorespiratory Cross-Correlation

Having screened out respiration-induced EDRs, we now present a filter to classify the remaining EDRs as voluntary (i.e., due to music imagery) or involuntary (i.e., due to auditory startle or spontaneous EDA fluctuations). The classification of EDRs into voluntary or involuntary
responses requires several assumptions. The source of some EDRs, such as those generated by a deep inspiration, can be verified from the record of other physiological signals. However, in most other situations, the source of the EDR is unknown, and we must classify the EDRs based on the assumption that the participant is fully compliant, engaging in the specified mental task. Thus, in this study, all EDRs generated during periods of rest were assumed to be involuntary, and all electrodermal reactions generated during periods of music imagery were assumed to be voluntary. The presented cardiorespiratory filter tracks respiratory sinus arrhythmia (RSA), a phenomenon whose physiological origins are still debated wherein heart rate fluctuations at respiratory frequencies are observed in healthy humans (Eckberg, 2009; Karemaker, 2009). The filter is based on the premise that we will observe a momentary lapse in the RSA of an individual during the generation of voluntary EDRs; in other words, voluntarily generated EDRs will be accompanied by a marked decorrelation between heart rate and respiration. The proposed method creates a statistical model of the expected correlation of the heart rate and respiration data while the individual is at rest, and using bootstrap prediction bands, determines whether a significant decorrelation between the two signals has occurred. This decorrelation is attributed to non-respiratory influences including the imagery and startle responses of the participants.

Let \( R(t), 0 \leq t \leq T \) represent the raw respiration signal, where \( T \) is the duration of the signal in seconds. Instantaneous heart rate, \( HR(t) \), in beats per minute (bpm), was computed by inverting the interbeat intervals extracted from the raw blood volume pulse (BVP) signal. The first derivative of the respiration signal \( R'(t) \) was estimated by the first difference of the sampled version of \( R(t) \). The relative heart rate changes, \( HR'(t) \), were calculated as follows,

\[
HR'(t) = \frac{100(HR(t + \delta) - HR(t))}{HR(t)} \quad 0 \leq t \leq T - \delta
\]  

(3)

where \( \delta \) is defined as in equation 1. Both \( HR'(t) \) and \( R'(t) \) were standardized to 0 mean and unit variance, yielding in \( HR_z(t) \) and \( R_z(t) \), respectively.

The two second cross-correlation in the \( m^{th} \) segment, \( C_m(t) \), between \( HR_z(t) \) and \( R_z(t) \) was calculated as
\[ C_m(t) = \int_{-1}^{1} HR_z(t + s) R_z(s) ds \]  

(4)

where \( m - 1 \leq t \leq m + 1, m = 1, 2, \ldots, M \) and \( M = \lceil T - \delta \rceil - 1 \) with \( \lceil \cdot \rceil \) denoting the ceiling function (Ralston & Reily, 1995). In other words, the cross-correlation between \( HR_z(t) \) and \( R_z(t) \) is calculated within a two-second sliding window with 50% overlap between successive windows. In the above, \( C_1(t) \) is the cross-correlation between \( HR_z(t) \) and \( R_z(t) \), from 0 to 2 seconds; \( C_2(t) \) is the cross-correlation between the same two signals from 1 to 3 seconds, and so on. Note that \( HR_z(t) \) and \( R_z(t) \) signals change over similar timescales so that their cross-correlation is meaningful.

Therefore, for a signal of duration \( T \) seconds, we will have \( T \) two-second cross-correlation curves. These \( T \) curves generated from the resting trial data were assumed to represent the typical correlation between heart rate and respiration in the absence of both environmental and internal stimuli. Following the formulation of Lenhoff et al. (Lenhoff et al., 1999), we use these resting trial correlation curves to generate a resting model for the cardiorespiratory correlation, and use prediction bands to determine whether or not a test correlation curve belongs to the same population from which the resting curves were generated. If the test curve falls within the prediction bands, i.e., belongs to the population of resting trials, we conclude that the individual was in a resting state; if the test correlation curve falls outside of the prediction band, we conclude that the individual was affected by an internal or external stimulus. The cross-correlation curves are low harmonic curves, consequently, this method is reliable using as few as 25 curves (Lenhoff et al., 1999); the authors recommend a minimum of \( T = 30 \) seconds to generate a valid population model. The generation of the population model and the prediction bands is detailed below.

### 8.3.4.3.2 Generation of resting correlation curve model

The \( T \) curves generated from the resting trials are viewed as perturbations of a true curve that can be represented by the finite Fourier sum:

\[ f(t) = \mu + \sum_{k=1}^{K} (\alpha_k \cos(2\pi kt) + \beta \sin(2\pi kt)) \]  

(5)
where $K$ is 512, and $0 \leq t \leq T$. In equation (6), $\mu$ is a constant that represents the overall mean of the cardiorespiratory correlation curve, and the form of $f(t)$ stipulates that $f(0) = f(T) = \mu$. For each correlation curve, $C_m(t)$, we compute its Fourier representation $\hat{C}_m(t)$ as follows

$$\hat{C}_m(t) = \mu_m + \sum_{k=1}^{K} (\alpha_{m,k} \cos(2\pi kt) + \beta_{m,k} \sin(2\pi kt)) \quad m = \{1, 2, 3, \ldots, T\}$$

(6)

where $\alpha_{m,k}$ and $\beta_{m,k}$ are the coefficients for the Fourier approximation of the $m^{th}$ curve. For each $\hat{C}_m(t)$, we gather these fitted coefficients into a vector $W_m$ of length $2K + 1$:

$$W_m = [\mu_m \alpha_{m,1} \ldots \alpha_{m,K} \beta_{m,1} \ldots \beta_{m,K}]$$

(7)

The means of each of the coefficients in the $T$ instances of $W_m$ ($1 \leq m \leq T$) were calculated and gathered into a $1 \times (2K + 1)$ vector denoted $\bar{W}$,

$$\bar{W} = \frac{1}{M} \sum_{m=1}^{M} W_m$$

(8)

and we also define vector $\ell(t)$ of length $2K + 1$,

$$\ell(t) = [1, \cos(2\pi t), \sin(2\pi t), \ldots, \cos(2\pi K t), \sin(2\pi K t)]$$

(9)

From these two vectors, the sample mean curve $M(t)$ can be estimated as

$$M(t) = \bar{W}^t \cdot \ell(t)$$

(10)

where the superscript $t$ denotes the transpose. The variability of $M(t)$ is represented by $S(t)$ and defined as,

$$S(t) = \sqrt{\frac{1}{M} \sum_{i=1}^{M} \ell(t)^{\dagger} (W_i - \bar{W}) (W_i - \bar{W})^t \ell(t)}$$

(11)

The mean and variability curves, i.e., $M(t)$ and $S(t)$, define the resting curve model for the participant.
8.3.4.3.3 Generation of prediction bands

Now that we have a resting cardiorespiratory correlation curve model, we need to define its boundaries of membership. In other words, when do we consider a correlation curve as belonging to the resting model? One way to define this membership is to construct prediction bands around the mean curve (Duhmael et al., 2004; Lenhoff et al., 1999; Murray-Weir et al., 2003), such that curves lying within the prediction bands are considered as belonging to or arising from the resting model.

The following procedure is used to generate prediction bands. As above, suppose that we have $M$ cross-correlation curves between resting heart rate and respiration signals. We randomly select a bootstrap sample of $M-1$ curves, with replacement, from this population of $M$ resting correlation curves. This is repeated $N_B$ times, where $N_B >> 1$. For the $i^{th}$ bootstrap sample, $i = 1, ..., N_B$, we calculate the mean and variability curves, $M_i(t)$ and $S_i(t)$, as in equations (10) and (11). For each bootstrap sample, let $\hat{C}_j(t)$ represent the Fourier approximation to the cross-correlation between the $j^{th}$ respiration and heart rate signals, $j = 1, ..., M - 1$. We then calculate the standardized difference, $D_{ij}(t)$, between the $j^{th}$ curve, $\hat{C}_j(t)$, from the $i^{th}$ bootstrap sample and the mean curve of the same bootstrap sample, $M_i(t)$,

$$D_{ij}(t) = \frac{|\hat{C}_j(t) - M_i(t)|}{S_i(t)} \quad j = 1, ..., M - 1$$

(12)

For the $i^{th}$ bootstrap sample, $i = 1, ..., N_B$, we obtain $D_i^*$ as the maximum difference over all $M-1$ curves, over time.

$$D_i^* = \max_j \{\max_t D_{ij}(t)\}$$

(13)

Given a desired confidence level $100(1-\alpha)\%$, we chose the constant $\theta$, so that

$$P\{\max_i D_i^* \leq \theta\} = 1 - \alpha$$

(14)
where \( \alpha \) is 0.05 in the present study. In other words, \( \theta \) is chosen such that there is a 95% probability that the maximum standardized difference between any curve and the mean curve is less than or equal to \( \theta \). Finally, the upper and lower 95% prediction bands were calculated as

\[
U(t) = M(t) + \theta \times S(t) \\
L(t) = M(t) - \theta \times S(t)
\]

(15)

where \( M(t) \), \( S(t) \) and \( \theta \) are given by equations (10), (11) and (14), respectively. Any correlation curve bounded by \( U(t) \) and \( L(t) \) is considered as arising from the resting curve model given by \( M(t) \) and \( S(t) \). A resting model and the associated prediction bands were estimated individually for each participant.

8.3.4.3.4 Testing the membership of unknown cardiorespiratory data

For a given participant, each two seconds of cardiorespiratory data from the non-resting trials (blocks B, C, and D) were tested against the prediction bands of the resting model, thereby determining whether or not these data resembled the resting cardiorespiratory correlation curves. In essence, we are thus determining whether or not external influences are mediating cardiac activity.

For each \( T \) seconds of data, where \( T \) represents the total length of the trial in seconds, we calculate \( Q(s) \), \( 0 \leq t \leq T \) and \( t - 1 \leq s \leq t + 1 \), which is the Fourier approximation to the cross-correlation between a two second segment of \( HR_z(t) \) and the corresponding two second segment of \( R_z(t) \) from a non-resting trial. We then calculate the standardized difference, \( D(s) \), between the unclassified correlation curve and the resting mean curve,

\[
D(s) = \frac{|Q(s) - M_R(s)|}{S_R(s)}
\]

(16)

where \( M_R \) and \( S_R \) are the mean curve and the standard deviation curves estimated from the resting trials. If the maximum absolute standardized difference from the resting mean, \( \max_s D(s) \) is less than or equal to \( \theta \), that is, the unclassified correlation curve is bounded by the upper and lower prediction bands, then the test segment of data is classified as resting state.
Otherwise, the test segment is considered as being influenced by external processes. For convenience, we created an indicator pulse spanning the duration of the test signal,

\[
I(t) = \begin{cases} 
0, & \max_s D(s) \leq \theta \\
1, & \text{otherwise} 
\end{cases}
\]

where, as before, \(0 \leq t \leq T\) and \(t - 1 \leq s \leq t + 1\). This indicator function is used in Section 4.4 to determine the source of a single, observed EDR.

### 8.3.4.4 Classifier Evaluation

All detected EDRs were subsequently validated by visual inspection. In addition, each electrodermal activity signal was visually inspected for undetected EDRs. Here, an EDR was defined as an increase in the EDA signal of over 0.02 \(\mu S\) within five seconds. When the automatic detection algorithm flagged an EDR, the heart rate and respiratory signals were segmented beginning two seconds preceding the onset of EDR detection and ending one second following the onset of EDR detection. This window was chosen to account for the difference between the latency of the heart rate response (0.25 to 2 seconds) (Florian, Stancak, & Pfurtscheller, 1998), and the latency of an electrodermal response (1.3 to 2.5 seconds) (Prokasy & Raskin, 1973). Segmentation thus yielded a 3 second segment for analysis by the cardiorespiratory classifier described in Section 8.3.4.3, generating a corresponding indicator function \(I(t)\). If \(I(t) = 1\) (i.e., significantly different from the resting model) at any time within the segmented signal, the detected EDR was classified as voluntary, otherwise, it was classified as involuntary. For each subject, the number of true positives (TP), i.e., correctly classified voluntary reactions, including EDRs generated by a deep inspiration; true negatives (TN), i.e., correctly classified involuntary reactions, including EDRs generated from a startling stimulus; false positives (FP), i.e., incorrectly classified voluntary reactions; and false negatives (FN), i.e., incorrectly classified involuntary reactions were recorded. From these values, the positive predictive value (PPV), negative predictive value (NPV) and overall accuracy of the classifier were calculated.

Classification results were compared for EDRs generated during trials conducted in silence and trials conducted in the presence of a background noise. These two conditions were compared
with a Pearson’s chi-squared test (df = 1) to determine whether classification accuracy differed significantly between trials conducted in the presence and absence of background noise.

8.4 Results

8.4.1 Automatic EDR Detection

In all the signals across all subjects, 100% of the EDRs present in the signals were detected, and no false positives were generated. The number of detected EDRs varied between participants; these results are presented in Table 8-3.

Table 8-3 Individual cardiorespiratory classifier parameters

<table>
<thead>
<tr>
<th>Subject</th>
<th>Number of Detected EDRs</th>
<th>Respiratory Threshold (ψ)</th>
<th>Cardiorespiratory Threshold (θ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>1</td>
<td>74</td>
<td>0.004</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0.004</td>
<td>0.009</td>
</tr>
<tr>
<td>3</td>
<td>111</td>
<td>0.004</td>
<td>0.008</td>
</tr>
<tr>
<td>4</td>
<td>57</td>
<td>0.003</td>
<td>0.014</td>
</tr>
<tr>
<td>5</td>
<td>88</td>
<td>0.003</td>
<td>0.009</td>
</tr>
<tr>
<td>6</td>
<td>31</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>8</td>
<td>33</td>
<td>0.003</td>
<td>0.016</td>
</tr>
</tbody>
</table>

8.4.2 Respiratory and Cardiopulmonary Filter Parameters

The respiratory and cardiopulmonary patterns varied significantly between participants. As a result, the threshold values $\psi$ for the respiratory filter and $\theta$ for the cardiorespiratory filter were unique to each individual; these values are listed in Table 8-3.
8.4.3 Classification Results

PPV and NPV for each participant were calculated according to the truth set defined by the rules presented in Section 8.3.4.4. These results along with the overall accuracy of single EDR classification are presented for each participant in Table 8-4.

Table 8-4  Cardiorespiratory filter classification results

<table>
<thead>
<tr>
<th>Participant</th>
<th>PPV</th>
<th>NPV</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77%</td>
<td>93%</td>
<td>80%</td>
</tr>
<tr>
<td>2</td>
<td>79%</td>
<td>82%</td>
<td>80%</td>
</tr>
<tr>
<td>3</td>
<td>82%</td>
<td>74%</td>
<td>78%</td>
</tr>
<tr>
<td>4</td>
<td>71%</td>
<td>73%</td>
<td>72%</td>
</tr>
<tr>
<td>5</td>
<td>69%</td>
<td>71%</td>
<td>72%</td>
</tr>
<tr>
<td>6</td>
<td>94%</td>
<td>92%</td>
<td>90%</td>
</tr>
<tr>
<td>7</td>
<td>82%</td>
<td>86%</td>
<td>83%</td>
</tr>
<tr>
<td>8</td>
<td>67%</td>
<td>83%</td>
<td>70%</td>
</tr>
<tr>
<td>Average</td>
<td>78 ± 9%</td>
<td>81 ± 7%</td>
<td>78 ± 7%</td>
</tr>
</tbody>
</table>

Examples of classified trials are presented in Figure 8-4. Figure 8-4a presents a trial wherein the individual alternated between 20 second periods of rest and activity. In this trial, each detected EDR was correctly classified with the exception of that generated in the final imagery period. Figure 8-4b presents a baseline trial during which startling noises are presented; four of the five audio stimuli produced a startle EDR, all of which were correctly classified as involuntary reactions. The classifier also correctly identified the two spontaneous EDRs in this trial as involuntary. In Figure 8-4c, the participant alternated between rest and music imagery while audio stimuli were presented at random intervals; two of the audio stimuli (at 10s and 72s) generated EDRs, which were correctly classified as involuntary. Voluntary EDRs were correctly classified in all imagery periods with the exception of the EDR at 100s. All involuntary EDRs were also correctly identified.
Figure 8-4 Classification of EDRs within: a) an imagery trial (Block B); b) a quiet resting trial with startles (Block C); and c) an imagery with startles trial (Block D). Solid vertical lines denote the times at which audio startles were presented.
8.4.4 Effect of Presence of Background Noise

Trials conducted in silence were compared to trials conducted in the presence of low-level background noise for each participant. Table 8-5 illustrates that for all except one participant, there was no significant difference in classification accuracy. However, for participant 2, EDRs generated during trials conducted without background noise were more accurately classified ($p = 0.02$) than those generated in the presence of background noise.

**Table 8-5** Accuracy of classifying EDRs generated with and without background noise

<table>
<thead>
<tr>
<th>Participant</th>
<th>Without background noise (total # EDRs)</th>
<th>With background noise (total # EDRs)</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75.3% (60)</td>
<td>92.9% (14)</td>
<td>0.517</td>
</tr>
<tr>
<td>2</td>
<td>85.7% (49)</td>
<td>71.0% (31)</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>75.9% (71)</td>
<td>77.5% (31)</td>
<td>0.84</td>
</tr>
<tr>
<td>4</td>
<td>69.4% (49)</td>
<td>67.5% (8)</td>
<td>0.27</td>
</tr>
<tr>
<td>5</td>
<td>71.0% (69)</td>
<td>73.7% (19)</td>
<td>0.01</td>
</tr>
<tr>
<td>6</td>
<td>91.3% (23)</td>
<td>87.5% (8)</td>
<td>0.61</td>
</tr>
<tr>
<td>7</td>
<td>78.7% (47)</td>
<td>80.7% (57)</td>
<td>0.25</td>
</tr>
<tr>
<td>8</td>
<td>70.0% (20)</td>
<td>69.2% (13)</td>
<td>0.95</td>
</tr>
</tbody>
</table>


8.5 Discussion

This study proposes a method of classifying single EDRs as voluntary or involuntary by utilizing cardiorespiratory signals that are recorded simultaneous with electrodermal activity. Distinguishing between resting and active states without the help of the classifier would require the assumption that all observed EDRs were generated due to mental imagery. In this situation, classification of the EDA signal would decrease in accuracy from $79 \pm 7\%$ to $50 \pm 8\%$, demonstrating that a cardiorespiratory classifier based on the respiration length line and the cross-correlation of heart rate and respiration significantly improves the ability to determine the source of an observed EDR.
8.5.1 Classification Assumptions

However, the participants recruited to this study were not trained in mental control techniques, such as meditation. Therefore, it is likely that at some point during the periods of rest, the participants’ minds were not entirely cleared, and a mentally stimulating thought caused an EDR. This EDR would be preceded by a decorrelation between the respiratory and cardiovascular signals, as it was voluntarily generated by the mental stimulus. However, as it occurred during the resting period, this EDR would be considered misclassified under the assumption that all EDRs generated during a resting period were involuntary. The converse situation may also occur; spontaneous EDRs are generated 7.5 times every minute in the average population (Malmivuo & Plonsey, 1995); it is likely that during an imagery period, the participant experienced a spontaneous EDR that was not preceded by a decorrelation between respiratory and cardiovascular patterns. The presented classifier would correctly label this reaction as involuntary, yet under the study assumptions, this classification would be erroneous, as the EDR occurred during an imagery period. While the authors recognize this problematic situation, data have not been gathered to provide any further information on the true source of the electrodermal reaction. Consequently, the assumption of full compliance to the required mental task is necessary, though as a result, the accuracy of the presented classifier is likely underestimated.

One recurring situation highlights the potential classification errors due to this assumption. Often, when cued to switch from a period of music imagery to a period of rest (ex. during experimental blocks B and D), an electrodermal reaction is generated within the first five seconds of the rest period, and is classified as a voluntary reaction. As it occurs during a rest period, this EDR is considered to be a false positive. However, many participants reported that it was difficult to stop the music imagery process on cue, and that the act of ceasing to perform music imagery required more effort than initiating music imagery. This effortful act of abruptly terminating music imagery may well result in a voluntary EDR as the resting process is initiated. Taking this into consideration, if EDRs that occur within the first five seconds of an imagery to rest transition are considered voluntary, the positive predictive value significantly increases from $77\% \pm 8.7\%$ to $87\% \pm 8.7\%$ ($p = 0.04$), illustrating that the current reported classification accuracy is likely an underestimation of the true performance of the classifier.
8.5.2 Effects of Background Noise and Time

In their 1963 study on animal startle reactions, Hoffman and Flesher serendipitously discovered that the background noise they were using to mask unpredictable environmental sounds in fact had an enhancing effect on startle reactivity in the rat (Hoffman & Fleshler, 1963). This result has been replicated many times, and recently, the same phenomenon of increased startle reactivity during increased background noise has been demonstrated in humans (Flaten et al., 2005). In the context of these previous studies, it is intriguing that the results indicate that for seven of the eight participants, the classifier performs equally well for startle EDR generated under both conditions. This can potentially be explained with Holand’s finding that a component of the overall startle response included an increase in blood pressure and heart rate (Kamiya, 1971). The results from this present study suggest that while the magnitude of the startle reaction may be enhanced in the presence of background noise, the classifier remains robust against these changes, and is able to perform equally well under both conditions. In the case of participant 2, the classifier performed significantly better under conditions of silence. This difference may be attributed to either: a) distraction from the music imagery task in the presence of background noise or; b) a different pattern of cardiovascular startle response in the presence of background noise for this particular individual. Further investigation of this participant’s responses to determine the source of the preferential classification is warranted.

8.5.3 Limitations

While the ability for the classifier to distinguish between voluntarily and involuntarily generated EDRs appears promising, the results must be interpreted in light of the limitations of the study design. The classifier was tested on eight, able-bodied individuals within a narrow age range, who may not have demonstrate significant differences in their patterns of electrodermal activity. This is illustrated in the fact that parameter D, the threshold for detecting an EDR, which was determined from one randomly chosen subject was 100% suitable for the remaining 7 subjects. Electrodermal activity has been known to vary with age, and among individuals with different disabilities. Further studies are needed to determine suitable parameter values for EDR detection in individuals outside the demographics of those who participated in this study. Furthermore, all physiological signals were recorded under controlled environmental conditions (minimal radio frequency interference). The values of the parameters presented in this study are thus specific to
uncontaminated physiological signals. Application of the proposed classifier amid noisy experimental conditions would require specific removal of the offending artefacts.

8.5.4 Significance of Study

In fields where electrodermal activity is used as a measure of the state of an individual’s sympathetic nervous system, some means of artifact control must be employed to determine the source of the EDRs (i.e. whether they are voluntarily or involuntarily generated). Until now, these methods have not existed, with the exception of a recently-developed standardized rule-base that utilizes visual inspection of a respiratory signal to determine whether or not an EDR is a respiratory artefact (Schneider et al., 2003). While useful for identifying EDRs that were generated from changes in respiration, these rules do not distinguish voluntary from involuntary EDRs. As there is no existing means of making this distinction, every discipline makes different generalizing assumptions about the source of the observed EDRs. In the field of polygraphy, all electrodermal reactions are assumed to be involuntary, and indicative of the subject’s unconscious reactions, despite evidence illustrating that mental exercises are an effective countermeasure and can be used to voluntarily generate EDRs to bias the results (Ben-Shakhar & Dolev, 1996). In the field of access technologies, all electrodermal reactions generated are assumed to be voluntary, in spite of a priori knowledge that spontaneous EDRs occur at an average rate of 7.5 per minute (Malmivuo & Plonsey, 1995). Fields of study that include electrodermal activity as a measure of sympathetic arousal may benefit from using the proposed classifier to obtain greater insight into the source of observed EDRs, provided that the relevant cardiorespiratory signals can be simultaneously obtained.

8.6 Conclusions

This paper has proposed a method for classifying EDRs using simultaneously recorded cardiac and respiratory signals. The presented classifier tracked both the RLL over a five second moving window, and the cross-correlation between the respiratory and heart rate signals, to distinguish voluntary EDRs due to an irregular breath or mental imagery, from involuntary EDRs associated with startle reactions or a spontaneous increases in EDA. This classifier had a positive predictivity of 78%, a negative predictivity of 81%, an overall accuracy of 79%, and, with the exception of one subject, performed equally well under conditions of silence and background noise. This is nearly a 30% improvement in accuracy over the case when all EDRs are naively
assumed to be voluntarily generated. Our results suggest that the cardiorespiratory classifier may
be useful for EDA research, such as polygraphy or alternative access for individuals with
disabilities, where the source of single EDRs is of particular interest, and illustrate that
physiological signals respond differentially to changes in the auditory environment.
The coda of this thesis is written for the same purpose as a coda is written for a piece of music – to bring the ideas presented in the body of the work to their structural conclusions; to provide a framework within which to look back upon the main body; to allow the audience to absorb what has been presented, and; to create a sense of balance. The ideas presented in the body of this thesis have been segregated into two themes: the physiological effect of a person on their environment, and the effect of the environment on the physiology of a person. The coda begins with the presentation of an idea that merges these two themes for the first time in the thesis by exploring the idea of physiologically-generated music – a means of interacting with the environment that has the potential to change the environment’s understanding of an individual’s role and identity. The conclusions of this thesis are then stated in light of the three research questions, the contributions of this thesis are re-examined, and the thesis concludes with recommendations and future directions for research in the area of physiologically-mediated interaction between the profoundly disabled and their environment.
9.1 Soundprints of the Profoundly Disabled: The Promise of Physiologically-Generated Music

Advanced medical technologies have increased the prevalence of children and adults who require lifelong complex continuing care to survive (Carnevale et al., 2008). As a result of catastrophic injuries or pathologies, many have minimal or no ability to move or speak and remain entirely dependent on respiratory and nutrition technology and multiple human caregivers. Most of these individuals have cognitive abilities that are severely damaged or unknown, and they are considered unresponsive to their environment. The profound responsibilities and implications of supporting these people are just being realized, because until about 20 years ago, people this dependent did not exist. Essentially, improvements in medical technology have created “a new strain of human beings” (Brown, 2009) who require an unprecedented level of care. Despite the extraordinary physical, psychological, social and financial challenges involved in supporting these persons, most are cherished by their families, regardless of whether they are cared for in their homes or in institutional long-term care settings (Carnevale et al., 2008). However, their inability to communicate, or respond, places substantial strain on the family and other caregivers. Caregivers perceive communication to be unidirectional, and experience considerable distress and frustration associated with voicelessness and unresponsiveness (Happ, 2001). Moreover, the recognition of unique personhood is difficult to achieve with interactionally unavailable persons such as these. At a time when the ethical debates regarding this growing population are gathering pace, it is important to reflect upon and examine our response to the most profoundly impaired and vulnerable members of our society. We endeavor to address this matter by proposing an intervention that may enable the profoundly disabled to communicate their human uniqueness, and enable others to respond to them in an individualized manner: the generation of music from physiological signals.

According to social interactionist theory, the existence of the human self hinges on successful interaction with others (Cooley, 1972). Personhood is defined as ‘a standing or status that is bestowed upon one human being by others, in the context of relationship and social being’ (Kitwood, 1997). Thus, devoid of the ability to engage in social interaction, the personhood of
voiceless, motionless individuals is absent or severely impaired. Caregivers often confine their interaction to nursing, therapies or custodial care, as unreciprocated social interaction seems futile. In essence, the profoundly disabled are often not perceived as an “other” with whom interaction is possible because they do not demonstrate putative cardinal human attributes of co-presence and reciprocity (Waksler, 2006). In the absence of embodied and socially interconnected manifestations of self, perceiving the unique humanness of these individuals is fraught with challenges and may not be accomplished (Kontos, 2005). This has significant ramifications for the quality of life of such persons and those who care for them.

To date, only a few interventions have addressed quality of life and quality of support issues for people with profound disabilities. These interventions have predominantly consisted of presenting preferred items, stimuli or activities that increase the prevalence of happiness indices in the profoundly disabled, or in training direct support staff in techniques to increase the quality and quantity of their interactions with those for whom they are caring (Maes, Lambrechts, Hostyn, & Petry, 2007). Supported by the idea that identity is shaped in the interaction between the person and the environment (Jahiel & Scherer, 2009), these interventions are promising in theory. However, the majority of studies report only moderately positive effects of these interventions on caregiver and/or client behavior (Maes et al., 2007). This is likely due to the expressive repertoire of the motionless, voiceless individual, which is so severely limited that any interaction relying on their physical behaviors is constrained from the outset.

In light of this overwhelming constraint, we look towards physiological rather than physical responses to enable interaction with the environment. It is well known that physiological signal changes in the autonomic nervous system are connected to emotional states (Ekman et al., 1983). These connections are subtle and nuanced, and the status of expressive physiology in the emotional response hierarchy is debatable (James, 1992; Schachter, 1964). In spite of these challenges, much work has been conducted to classify emotion according to patterns in physiological signals (Picard et al., 2001). Information about physiological and emotional state represented by the patterns of change in these signals traditionally has been displayed visually, but recently, there has been growing interest in displaying this information through sound. Enabling others to hear the physiological signals of the profoundly disabled may afford caregivers access to the changing emotional states of these individuals.
Physiological signals can be mapped to musical elements such as pitch, rhythm and key, enabling a listener to “hear” changes in an individual’s internal state and emotions. For example: changes in the absolute values of electrodermal activity levels can be mapped to intervals between musical pitches, thereby creating a melody line; frequency of respiration can be mapped to the articulation and phrasing of the melody; and heart rhythms can be mapped to the tempo of the music. Such auditory representations have been applied to date primarily for clinical and artistic purposes (Benovoy et al., 2007). Clinically, physiological signals and sound have been combined for the purposes of sonification - an auditory means of conveying and perceiving information. Sonification of electroencephalography (EEG) signals, for example, has been useful for fast screening of long-term EEG recordings, and real-time monitoring of EEG recording sessions (de Campo, Hoeldrich, & Eckel, 2007). Artistically, physiological signals and sound have been combined to create interactive art performances that are based upon the physiological state of performers. Arslan (Arslan et al., 2005) and Brouse (Brouse et al., 2006) provide a full review of both biosignal sonification and physiologically-driven musical interfaces.

We propose a new purpose for combining sound and physiological signals: using music generated from the changes in the physiological signals of the profoundly disabled to communicate a state of being and personhood. We hypothesize that music – a universal medium - has the potential to convey identity, and form the basis of meaningful interaction with this silent population.

Music seems to be an optimal medium for communicating personhood, since musical sounds and rhythms constitute a universal nonverbal signifying system capable of expressing human emotion. While the emotional content of music is acknowledged by many music scholars, some posit that music can create an “emotional geography of relatedness” between individuals (Wood, 2002). It has been argued that “music - and our responses to it - is an expression of emotions and drives that have the potential to recreate our social and spatial selves. These qualities are what make music about being and becoming, and to get to grips with this is to understand the way identities are made” (Wood, Duffy, & Smith, 2007). In the time-space where music is produced and heard, the intimate, emotional quality of human relations is laid bare. Performing music, therefore, is about intimate encounters with others, enabling participants to connect emotionally and to share a dimension of human experience beyond language, movement or gesture. Drawing
from the body of literature that connects changes in physiological signals of the human body to emotional state, the potential for physiologically-generated music to convey an individual’s state of being becomes clear. The autonomic nervous system in the profoundly disabled often remains intact despite damage to the somatic nervous system (Doble et al., 2003); in harnessing and manifesting changes in these signals through music, they can express the co-presence and reciprocity required for others to perceive them as interactionally responsive and available. We believe that physiologically-driven musical expression has the potential to allow these individuals to reveal a “soundprint”, which, like a fingerprint, is specific to individuals and a revelation of their unique identity.

There exist an enormous number of permutations of physiological signal features and musical elements. Our purpose here is not to explicate the realm of potential algorithms, but to draw attention to the possibility for inclusion in the human community by revealing the soundprints of the profoundly disabled through music produced from their physiological signals. Soundprints have the potential to modify the environmental milieu and soundspaces of these silent individuals and to enable others to recognize their unique embodiment. We strongly advocate for research towards this goal in the spirit of enriching interpersonal interactions with the profoundly disabled and of creating spaces of community and belonging.

Acknowledgment:

The authors are indebted to Shauna Kingsnorth and Elaine Biddiss for their contributions to the development of the ideas in this manuscript.
9.2 Research Questions

In this section, the research questions of this thesis are revisited, and conclusions are drawn in light of the collective results of the amassed research studies.

1) What challenges can be and remain to be overcome in teaching individuals with profound disabilities to use their autonomic physiological signals to interact with their environment?

The literature appraisal presented in Theme 1 variation 1 gathers strong evidence that illustrates that signals of the peripheral autonomic nervous system, namely, electrodermal activity, skin temperature, respiration and heart rate, can be brought under voluntary control. While the challenges of slow response time, metabolic noise and pathological change of these signals must be taken into consideration, the challenge of bringing these signals under voluntary mental control can be overcome. Research presented in Theme 1 variation 2 demonstrates that the challenge of developing computer algorithms that can accurately detect changes in electrodermal activity induced by mental and respiratory exercises can also be overcome. Challenges that remain to be overcome in teaching individuals with profound disabilities to use their autonomic physiological signals to interact with their environment are explored in Theme 1 variation 3. These challenges include the profound intra-subject variability of autonomic physiological signals, reliance on third-party interpretation to determine the preferences and responses of profoundly disabled children and the learned helplessness of children born with profound disabilities. It is critical that one addresses these challenges before physiological signals can successfully be used by children with profound disabilities to deliberately interact with their environment.

2) What are the outcomes (e.g. effects on life habits, mood) of giving a disabled child the ability to interact with his or her built environment?

The case study presented in Theme 2 variation 1 demonstrates that a relatively simple change in the built environment (e.g. the introduction of a switch controlled via tongue movement) can have a significant impact on multiple elements of activity and participation, as defined by the International Classification of Functioning and Health. In this case study, a change in the built
environment resulted in increased communication, new opportunities for interpersonal relationship and facilitated recreation, leisure and spiritual activities. These results illustrate the breadth of potential changes that can result from the introduction of a new modality of person-environment interaction, and inform future studies that endeavour to measure the impact of physiologically-mediated person-environment interactions in children with profound disabilities.

3) Do physiological signals of individuals respond differentially to specific changes in their social and auditory environmental milieux?

The results of the research studies presented in Theme 2, variations 2 and 3 demonstrate that signals of the autonomic nervous system exhibit differential responses to specific changes in the social and auditory environmental milieu. Physiological signals are a viable measure of the effect of a change in the social environment (e.g. the presence of a Therapeutic Clown) for children who are unable to move and speak. Furthermore, physiological signals demonstrate patterns of behaviour in response to changes in the auditory environmental milieu that can be differentiated from patterns induced by changes in internal mental state. Thus, signals of the peripheral autonomic nervous system can be used to both assess and process the effect of changes in the social and auditory environments of children with profound disabilities, providing a new modality to determine the influence of the environment on these silent children.

9.3 Contributions

In conclusion, the perceived contributions of this research (reiterating the enumeration presented in the Overture) are as follows:

1) Critical analysis and consolidation of literature across three disparate fields from the past 50 years pertaining to voluntary control of four autonomic nervous system signals. This literature appraisal rendered both a comprehensive understanding of the physiological systems associated with these four signals, and full panoramic of the methods used to bring them under voluntary control. Explicit discussion of the challenges associated with this field was undertaken to guide future research efforts (Blain, Chau et al., 2008).

2) Establishment of empirical evidence demonstrating that a signal of the autonomic nervous system - electrodermal activity - can be voluntarily controlled via mental and
respiratory activities. Two algorithms that can successfully differentiate an individual’s mental state based on patterns of electrodermal activity were developed and presented (Blain, Mihailidis et al., 2008).

3) Identification and substantiation of three key challenges in developing a physiological signal-based access pathway for profoundly disabled children based on a series of case studies with an individual with spastic quadriplegia. Empirical evidence from these case studies were used to consolidate challenges identified in the literature, and practical and concrete suggestions of how these critical issues could be addressed for future rigorous research regarding access pathways for profoundly disabled children were made.

4) Development of a custom-tailored bedside computer access solution using a person-focused approach to match an individual with profound disabilities to a technological solution. A multidimensional assessment toolbox was developed and employed to measure the effect of enriching the interaction between an individual and her environment, and was the first study to employ a multipronged approach to assessing the effect of access on the profoundly disabled (Blain, McKeever et al., 2010).

5) Measurement of the physiological, behavioural and emotional effects of therapeutic clowns on children in a long-term healthcare setting (Blain, Kingsnorth, & McKeever, 2010). This information is essential for establishing rigorous evidence of the positive effects of people in the environment of profoundly disabled children.

6) Construction of a multivariate algorithm to identify and classify changes in four signals of the autonomic nervous system (Blain, Kingsnorth, & Chau, 2010). This algorithm addressed the profound intra- and inter-subject variability of patterns of physiological signals, and was adaptable to analyzing significant change in autonomic state from a variety of physiological signal inputs.

7) Establishment of cardiac sinus arrhythmia as a means of distinguishing voluntarily from involuntarily generated patterns of electrodermal activity, and construction of a classifier that employed this phenomenon to automatically detect and distinguish electrodermal reactions (Blain, Power et al., 2010).
8) Formulation of a framework wherein the identity and personhood of children with profound disabilities can be constructed and modulated through physiologically-generated music. This framework outlines the theoretical underpinnings upon which future research in developing identity by enriching person-environment interactions can be developed.

9.4 Recommendations

As a result of this research, four strategies are highly recommended for research relating to physiologically-mediated interactions between a person and their environment.

9.4.1 Addressing the Challenges of the Target Population

There are a number of challenges unique to individuals with profound disabilities; several of these are explicitly addressed in Theme 1 Variation 3. Most physiological signal-based interaction pathways, regardless of whether they use peripheral ANS signals, EEG or near-infrared spectroscopy as the interactive signal, are developed and tested on the able-bodied population. In light of the challenges illustrated in this thesis moving from successful physiological signal interaction algorithms developed with the able-bodied population (Theme 1 Variation 2), to the challenge of applying these algorithms with a profoundly disabled child (Theme 1 Variation 3), it is highly recommended that strategies are implemented in the transition from one population to the next that address their divergent characteristics. Examples of these strategies include using Intensive Interaction (Nind & Hewett, 1994) to counteract the effects of learned helplessness in profoundly disabled children before beginning the training of physiological signal patterns. Other such strategies are detailed in Theme 1 Variation 3. The differences between profoundly disabled children and able-bodied adults must be explicitly addressed before deliberate physiologically-mediated interactions between profoundly disabled children and their environment can be realized.

9.4.2 Outcome Evaluation

In light of Jahiel and Scherer’s model of person-environment interaction in disability, it is recognized that changes in the built and social environment that enhance a child’s ability to interact with it will affect their life habits and mood, and may potentially bring to light different components of their identity as a person (Jahiel & Scherer, 2009). To fully understand the effect
of giving a child with profound disabilities the ability to interact with his or her environment, one must endeavour to capture this complex and broadly scoped range of changes. In addition to capturing technical details such as the transfer rate of the environmental interaction, it is recommended to examine the effect of the changes along the dimensions of the International Classification of Functioning and Health (ICF), particularly the dimensions of activity and participation, as was done in Theme 2 Variation 1 (Blain, McKeever et al., 2010), when examining the impact of any assistive technology for a person with disability. Only in including these dimensions when assessing the effect of any assistive technology can the true impact of the change be captured.

9.4.3 Intelligent Algorithms

Basic measurements of physiological signal states (e.g. heart rate, blood pressure) are often used as an indicator of the effect of various treatments and interventions. However, the absolute values of these signals, especially for children with profound disabilities, are often uninformative due to the tremendous inter- and intra-subject variability of the signal patterns. Additionally, the temporal patterns of and the correlations between the various physiological signals often contain more salient information than any single statistical value. It is strongly recommended that research investigating physiological signal change in response to various stimuli use intelligent algorithms that address these realities, such as the algorithms presented in Theme 1 Variation 2 (Blain, Mihailidis et al., 2008), Theme 2 Variation 2 (Blain, Kingsnorth, & Chau, 2010) and Theme 2 Variation 3 (Blain, Power et al., 2010). It is unlikely that data extracted from patterns of physiological signals of children with profound disabilities in lieu of considerations such as the ones addressed in these algorithms would be meaningful or accurate.

9.4.4 Triangulation of Different Sources of Data

Children with profound disabilities have an extremely limited repertoire of expressive behaviour. Interpretation of their physiological signal patterns is challenging due to the inability to explicitly confirm their mental or emotional state. Consequently, it is recommended that research directed towards augmenting or enriching the interaction between a child with profound disabilities and his or her environment using any physiological signals adopt the platform of collecting physiological, emotional and behavioural data, as was presented in Theme 2 Variation 2 (Blain, Kingsnorth, & McKeever, 2010). While all of these sources of data have limitations,
triangulation of the information gathered by both qualitative and quantitative methods has the potential to overcome their individual limitations, and allow a more holistic and accurate interpretation of the child’s reaction to their environmental milieu to emerge.

9.5 Directions for Future Research

Building upon the methods and results of this thesis, there are numerous directions for future research. A cross-section of potential directions is presented herein.

9.5.1 Creating Optimal Environments for Profoundly Disabled Children

Children with profound disabilities are rarely researched because they are considered especially vulnerable, and because their minimal interactivity with the environment makes it extremely challenging to collect meaningful data. As a result, virtually nothing is known about their lives, their experiences of embodiment, their relationships with their physical and social environment, and their experiences of various interventions and activities (Carnevale et al., 2008). Building upon the research presented in this thesis, patterns of physiological signals combined with other measures of behavioural and affective responses could potentially be used to assess the effect of different environments upon profoundly disabled children. This may provide evidence to be used to customize a child’s environment to match his or her preferences, thus giving their caregivers and interaction partners a better sense of the child’s identity.

9.5.2 Physiological Classification of Individuals

Data collected throughout the studies represented in this thesis and evidence from the literature indicate that every individual has a idiosyncratic physiological pattern of responding to their environment (J. I. Lacey & Lacey, 1958). Individuals tend to exhibit a stereotypical response in one or two dominant physiological signal pathways. One of the greatest challenges to overcome in the field of paediatric rehabilitation is the extreme heterogeneity of the target population; in the area of physiologically-mediated person-environment interaction, there are numerous conditions and pathologies that could cause a child to have profound disabilities, all of which present with varying physiological signatures. Even within a specific condition, such as severe spastic quadriplegia, the dominant physiological signal responses pathway and the patterns of those responses may vary from individual to individual. This tends to limit viable study design to case studies and single-subject research design (SSRD) (Logan et al., 2008). Building upon
evidence gathered in this thesis, one viable future research direction is to determine the efficacy of classifying individuals not according to the traditions measures of age, gender, disability, etc. but according to their dominant physiological response pathways. In investigating whether the patterns of physiological response remain constant within these categories, it may be feasible to classify individuals participating in physiologically-mediated person-environment research accordingly, enabling the development of study design with larger populations and allowing for the possibility of designs such as randomized controlled trials (RCT).

9.5.3 Emotion Recognition

Studies have demonstrated that it is possible to classify emotions in able-bodied adults using patterns of signals from the autonomic nervous system (Ekman et al., 1983; Picard et al., 2001). However, it remains challenging to determine emotion from the patterns of physiological signals of children, especially children with disabilities. While current directions of research aim to translate algorithms developed on able-bodied adults to recognize emotion in children with disabilities, future work may involve researching the effectiveness of translating emotion recognition algorithms developed on verbal children with disabilities to non-verbal children with profound disabilities. In training emotion recognition algorithms on a population with similar conditions and physiological patterns, but with the ability to confirm the emotional state they are experiencing, it may be possible to accurately detect emotion in the profoundly disabled, providing insight into their experiences of the world.

9.5.4 Technology and Self

Technology not only catalyzes changes in behaviour, but also changes in thought processes. Technology that enables individuals with profound disabilities to enrich their interactivity with the environment raises fundamental questions about selfhood, identity, community and what it means to be human. Further development of the idea presented in the coda of this thesis wherein physiological signals of the profoundly disabled are translated into identity-revealing music has the potential to become a platform upon which the fundamental questions of Science, Technology and Society (STS) may be explored. This platform may enable researchers to address questions of how technology affects what it means to be human, and how science and technology express the values of the society that we live in.
9.6 Closing Remarks

Disability and the habits and activities of daily life are formed in the bi-directional interactions between a person and his or her environment. For the growing number of the profoundly disabled children who do not have the ability to move or speak, this interaction is severely limited; consequently, these individuals lack both embodied and socially interconnected manifestations of self. The goal of this thesis was to investigate physiological signals as a means of exploring and enriching the interaction between a profoundly disabled child and his or her environment, and to contribute towards the ultimate goal of revealing the personhood and identity of the most vulnerable members of our society.
References


Appendix 1: Theme 2 Variation 2 Interview Transcripts

Q. Have you had computer access before this system? Why or why not?
A. No. Because I had no scanning system.

Q. Have you had environmental control before? Describe. Why did it not work?
A. Yes. For the TV, for the lights, for the phone. How does it work? Sip and puff. The lights flash and you select which one you want. Didn’t use it a lot at Bloorview. It wasn’t able to be hooked up. I could use the phone, but not the lights or the TV. Because the lights would be for the whole room, right? They would be hooked up to the whole room.

Q. What do you think of the following switches?
Sip and puff:
A. It works. I get short of breath.

Forehead:
A. I liked the idea of it. Because I could just use my eyebrows. I would get tired.

Tongue:
A. I don’t really get tired with the tongue switch.

Q. What’s important for you in a system that gives you access to the computer?
A. To communicate. To learn new things about the internet and search about new things. And to learn how to use QualityWord and Word. I’m comfortable with it now, I wasn’t in the beginning. I like it much better now – I find it much easier to work with.
Q. What do you like and dislike about this system in comparison to voice recognition systems (i.e. Dragon and HAL)?

A. Dragon: I don’t really remember it too much. HAL I can do the phone. Although… well, yes… I could use the phone and the music media player thing. I like the voice recognition. (How come?) It would be better for me if we could find a way that it doesn’t recognize the ventilator.

Q. What do you want to use your computer to do?

A. Writing, printing, it can already save, it can read, I can change my format. I want to use it to go to school, and to go to google. E-mail, oh yes, absolutely. I want to learn new things on the internet.

Q. What do you like about this current system right now?

A. It drags, and I can type, and I can save, and I can change the font, format, colour, underline, check e-mail, reply to e-mail, forward e-mail. I even learned how to forward now!

Q. What would you improve about it?

A. Make it easier. In terms of cool.

Q. Has it made a difference in your life? How?

A. Oh yes. Cause I’ve been here for almost 3 weeks now, and I’ve been on it all day, every day, checking my e-mail, writing back. If I didn’t have the computer, I’d be bored.

Q. What do use the internet for?

A. Searching for different places to live, different schools, different…. Anything.

Q. What would you like to use the internet for?

A. Ability online, which I wanted to show you today, because there’s a chat room, but my scanning thing won’t let me go into the chat room.
Q. What do you use word for?
A. Writing letters!

Q. What would you like to use word for?
A. Not sure.

Q. Overall, how do you feel about this system?
A. Very good. It’s a wonderful program. It’s easy to work with. Very easy to work with. It’s very good. I like it a lot. It makes me more independent.