CHOOSING INDIVIDUAL-SPECIFIC STIMULI TO CREATE DISTINCT AUTONOMIC STATES FOR COMMUNICATION

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INTRODUCTION

Since the early 1960s, there has been a growing interest in learning to control autonomic functions through operant conditioning. Early research in biofeedback and self-regulation strove to control disorders ranging from high blood pressure [1] to Raynaud's syndrome [2], and eventually led to research in the self-control of brain activity. This has given rise to the research field of brain-computer interfaces. Current brain-computer interfaces (BCI) use either cortically implanted or surface electrodes to monitor patterns of electrical activity in the brain [3]. Various features of these signals have been extracted and used to perform a variety of tasks, including moving a mouse cursor on a computer monitor in one and two dimensions, navigating a robot through a maze, and controlling a prosthetic hand [4], [5]. This interface has the potential to be used as a mode of communication by individuals with locked-in syndrome, a condition wherein an individual retains consciousness, but has both paralysis and anarthria. However, to date, there have been only a handful of clinical trials testing the efficacy of this means of communication for people with locked-in syndrome (LIS), and these have illuminated many disadvantages of the system, including long training periods, noisy signals, slow speeds, electrode and skin problems, the lack of aesthetic appeal for non-invasive BCIs, and the lack of acceptance in the target population and electrode rejection in invasive BCIs [6].

A potential alternative means of communication for people with LIS that ameliorates many of the disadvantages of both classes of BCIs is a system that tracks signals generated by changes in the state of the body's autonomic nervous system. The field of polygraphy has long-since demonstrated that autonomic signals such as skin conductance, blood pulse volume, heart rate, respiration rate and skin temperature change with mental activity, and that these changes can be reliably detected [7]. In addition to research in the field of biofeedback, recordings of these signals on athletes practicing mental imagery and on people practicing meditation further demonstrate that mental exercises generate machine-discernable changes in autonomic signals [8] [9].

Armed with this knowledge, we tested the ability of 6 able-bodied subjects to generate a discriminatory binary signal in their electrodermal activity via a combination of mental and breathing exercises. A classifier trained on the two activities that generated the largest difference in electrodermal activity was able to detect the correct binary state to an accuracy of over 80% for all 6 subjects [10]. While these results are encouraging, this classifier must be tested in clinical trials with locked-in individuals before the efficacy of this means of communication can be evaluated. The present study explores the first stage of this process, in which an individual with no previous means of communication is exposed to a variety of stimuli, to discern which generates the largest effect on his autonomic system. As illustrated in Figure 1, once two activities that create distinct changes are identified, a classification algorithm may be developed using a feature space of autonomic signals to discern the individual's mental state, enabling him to communicate.

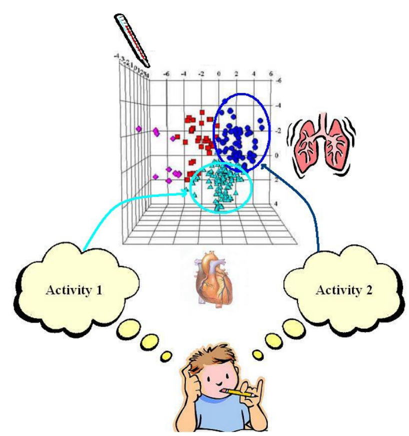

Figure 1: An individual thinking of different stimuli generates changes in his autonomic signals, for example, his respiration, heart rate and skin temperature. By choosing stimuli that generate distinct clusters in a unique autonomic signal feature space, a computer can classify the user's mental state to generate a binary output.

METHODS

Participant

A case study was conducted with a 13-year male with spastic quadriplegia. The participant is non-verbal, and currently has no reliable means of access to a computer, augmentative and alternative communication, or an environmental control system. His control challenges include asymmetrical tonic neck reflex, spacticity in his arms and legs, and frequent attempts to clear his airway by coughing. Ethical approval was obtained from Bloorview Kids Rehab and the University of Toronto to conduct this study.

Procedure

Prior to the recording session, it was delineated to the participant and his mother that the purpose of the session was to explore the effects of various stimuli on the participant's body signals. The signals would be analyzed offline and the participant would be called back for a second session to practice controlling his signals by thinking of the two stimuli that produced the largest reliable change. The mother was requested to bring along objects that affected a response from the participant (i.e. pictures of family members) and to generate a list of things that he liked and disliked.

On the day of the recording, the participant and his mother were brought into a quiet room with minimal external distractions. The sensors were attached to the participant, and a brief test trial was conducted to ensure that the equipment and software were calibrated and functioning correctly. The participant's baseline signals were recorded for the first 10 minutes of the 30-minute recording session, and the remainder of the session was used to record his reaction to affective stimuli provided by his mother. The participant was given approximately one minute to react to each stimulus, which included both things that he liked (ex. His pet) and things he disliked (ex. Going to the hospital). Stimuli were presented in random order, with each stimulus being presented twice within the session.

Equipment

A ProComp Infiniti multi-modality encoder from Thought Technology and a laptop computer were used to record electrodermal activity (EDA), blood volume pulse (BVP), respiration rate and skin temperature. EDA was recorded using a constant voltage 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, as illustrated in Figure 2. As depicted in the same figure, BVP was recorded by attaching an infrared sensor on the distal phalange of the participant's fourth finger, and skin temperature was recorded from a temperature sensor attached to the fifth finger. A glove was fitted over the participant's hand to hold the sensors in place and to prevent them from being dislodged due to spastic movements. A piezo-crystal respiratory effort sensor was secured over the subject's clothing around the thoracic area to measure respiration. BVP was sampled at 2048 Hz, and the remaining signals were sampled at 256 Hz. The signals were displayed in real-time on the computer screen. Audio recording of the entire session from a Nady CMB 40 Boundary Microphone was synchronized with the data collection, so that the changes in autonomic signals could be attributed to a specific stimulus.

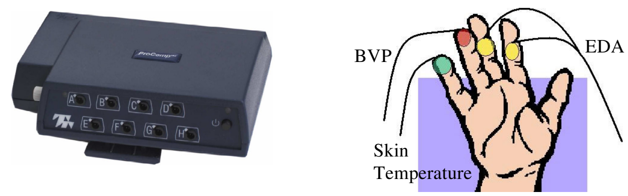

Figure 2: The ProComp Infiniti 8-channel data acquisition unit and the location of sensors on participant's non-dominant hand.

Data Analysis

The recorded signals were analyzed by extracting six salient features chosen based on evidence from the literature of their variability with an individual's mental state. From the EDA signal, the average skin conductance and the number of electrodermal reactions (EDR – increases in EDA over 0.05 µS within five seconds) per minute were calculated [11].

From the BVP signal, finger pulse waveform length (FPWL), a measure of the length of the signal line on a plot of BVP and time was calculated using equation 1:

$$FPWL = \sum_{i=1}^{SR*10} \sqrt{\left(\frac{1}{SR}\right)^2 + [y(i+1) - y(i)]^2} \qquad (1)$$

In this equation, SR is the sampling rate of the BVP signal, specifically 2048 Hz, and y is the BVP function over the discrete sampling intervals. The FPWL is a measure that combines the pulse rate and pulse amplitude; a decreased pulse rate and decreased pulse amplitude resulted in a shorter line length [7]. Since the line length is affected by the measurement's starting point, ten 10 s windows, each beginning 0.1 s after the previous one were used to calculate length line for an eleven second interval. The average of these 10 length measures yielded the FPWL over that period.

Similarly, from the respiration signal, the respiration line length (RLL) combines the measures of respiration amplitude and respiration cycle time, and has been frequently used in polygraph research [12]. The length measures were calculated using equation (1), where y now represents the respiration signal, from ten 10 s windows, each beginning 0.1s after the previous one. The average of each of these measures yielded the RLL over the eleven-second interval, and the RLL over all intervals comprising the given task was calculated.

From the temperature signal, the average temperature over the task period, and the temperature range over all 10-second intervals comprising the tasks were extracted. These features are summarized in Table 1.

Table 1: Features extracted from recorded data

Signal	Features extracted
Electrodermal Activity	1) Average skin conductance 2) Number of electrodermal reactions / 10s
Blood pulse volume	3) Finger pulse waveform length / 10s
Respiration	4) Respiration line length / 10s
Skin Temperature	5) Temperature average 6) Temperature range / 10 s

Each of these features was calculated for the baseline period and for both presentations of each type of stimulation. EDA and temperature were flagged as potential discriminators if visual inspection of the shape of the signal curves yielded marked differences between baseline and both tasks. Examples of curve differences are presented in Figure 3.

The remaining four features were flagged as potential discriminators if a student's t-test between the baseline and the average of the two tasks was significant at the level of $p = 0.05$. The two activities with the highest number of potentially discriminatory features were selected as the ones with the most potential to affect an autonomic reaction in the participant, and will be used in future studies to generate a controlled autonomic binary signal for communication.

RESULTS

Average signals from the baseline period are presented in Table 2.

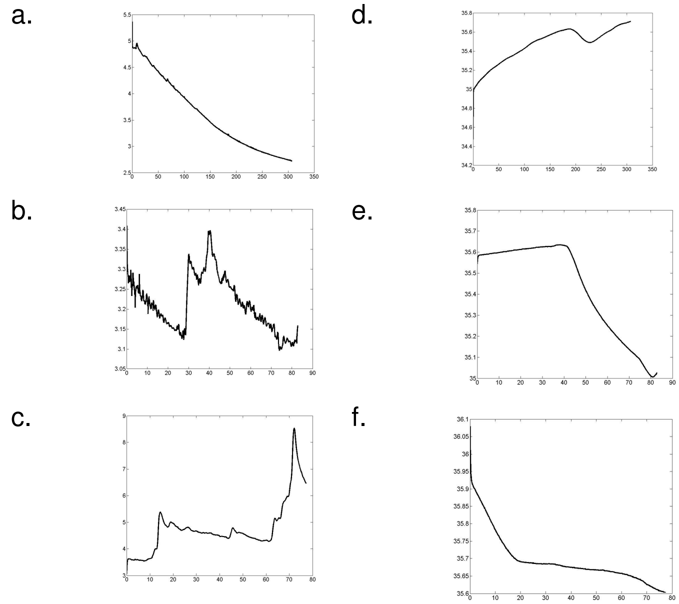

Figure 3: Shape of electrodermal activity and temperature curves during rest and during an activity. a) EDA during rest, b) EDA looking at family pictures, c) EDA listening to drums, d) skin temperature during rest, e) skin temperature looking at family pictures, f) skin temperature listening to drums.

Table 2: Signal averages for baseline period

Feature	Average (μ)	Standard Deviation (σ)
EDA	3.49	0.78
Number of EDRs / min	1.29	0.85
FPWL	559	121
RLL	17.4	2.0
Temperature	35.6	0.13
Temperature Range	0.036	0.07

Ten different stimuli were presented to the participant. The eight physical stimuli consisted of pictures of his dog, his family, a drum, a rainmaker, a pompom, a harmonica, his favourite toy and his respiration mask. In addition, two abstract stimuli were presented as his mother described to him going to bed, and his toothbrush. The features that were flagged as having the potential to discriminate between baseline and the task for each task are presented in Table 3, and the tasks with the most discriminating features are highlighted.

Table 3: Signal features with significant change from baseline

Stimuli	Features
Picture of dog	EDA, #EDR, FPWL
Picture of family	#EDR, temp, RLL, FPWL
Drum	EDA, #EDR, FPWL
Rainmaker	EDA, #EDR, FPWL
Toothbrush	#EDR, temp, FPWL
Mask	#EDR, temp, FPWL
Pompom	#EDR, RLL
Harmonica	EDA, #EDR, temp, FPWL
Going to bed	EDA, #EDR, temp, FPWL
Favourite toy	EDA, #EDR, FPWL

DISCUSSION AND FUTURE WORK

This study explores the effect of different stimuli on the autonomic nervous system of an individual with severe motor disability, restricting all previously attempted means of communication. Earlier investigations that explored whether or not able-bodied participants could produce computer-discernable changes in their autonomic state omitted this stage of the investigation. Clearly, able-bodied individuals could provide the investigators with feedback on whether they were performing the required task (ex. Mental arithmetic), and on the types of stimuli they found affective. As the participant in this study had no established means of providing feedback, it was necessary to empirically determine his reactions to a variety of stimuli that his mother believed had the potential to evoke a reaction.

In order for these stimuli to be used effectively as a means of generating a binary signal for communication, the participant must evoke the reaction intrinsically, as opposed to extrinsically via an external object or another individual's voice. There is no evidence that a strong autonomic reaction due to an external stimulus correlates to the strength, or even the type of reaction that would be generated by a self-motivated intrinsic reaction to the thought of that stimulus. However, it has been demonstrated in the literature that the strength of an autonomic reaction correlates with the strength of the emotional effect of a thought [13]. In order to overcome the challenge of being unable to receive feedback from the individual, this session was used to identify stimuli with the highest potential of to invoke an intrinsic reaction. In future sessions, the participant will be asked to think about the three stimuli that were most effective in the current session to determine whether or not changes in his autonomic reactions can be observed and classified. If this is successful, his autonomic system can become a controllable binary switch that will enable him to interact with his environment.

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