34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Wearable Wireless Sensor Platform for Studying Autonomic Activity and Social Behavior in Non-Human Primates

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Abstract — **A portable system has been designed to enable remote monitoring of autonomic nervous system output in non-human primates for the purpose of studying neural function related to social behavior over extended periods of time in an ambulatory setting. In contrast to prior systems which only measure heart activity, are restricted to a constrained laboratory setting, or require surgical attachment, our system is comprised of a multi-sensor self-contained wearable vest that can easily be transferred from one subject to another. The vest contains a small detachable low-power electronic sensor module for measuring electrodermal activity (EDA), electrocardiography (ECG), 3-axis acceleration, and temperature. The wireless transmission is implemented using a standard Bluetooth protocol and a mobile phone, which enables freedom of movement for the researcher as well as for the test subject. A custom Android software application was created on the mobile phone for viewing and recording live data as well as creating annotations. Data from up to seven monkeys can be recorded simultaneously using the mobile phone, with the option of real-time upload to a remote web server. Sample data are presented from two rhesus macaque monkeys showing stimulus-induced response in the laboratory as well as long-term ambulatory data collected in a large monkey cage. This system enables new possibilities for studying underlying mechanisms between autonomic brain function and social behavior with connection to human research in areas such as autism, substance abuse, and mood disorders.**

Index Terms **— autonomic, behavior, neural function, wireless, mobile, primate, monitoring**

I. Introduction and Motivation

A. Mental Health

Mental health disorders are becoming an increasing proportion of our disease burden and health care cost. Furthermore, mental health disorders are strongly related to the occurrence, successful treatment, and course of many chronic diseases [1]. These disorders can be relatively common and encompass a wide range of pathologies, ranging from Autism Spectrum Disorder (ASD), anxiety, and sleep disorders, to substance abuse, addictions, and clinical depression.

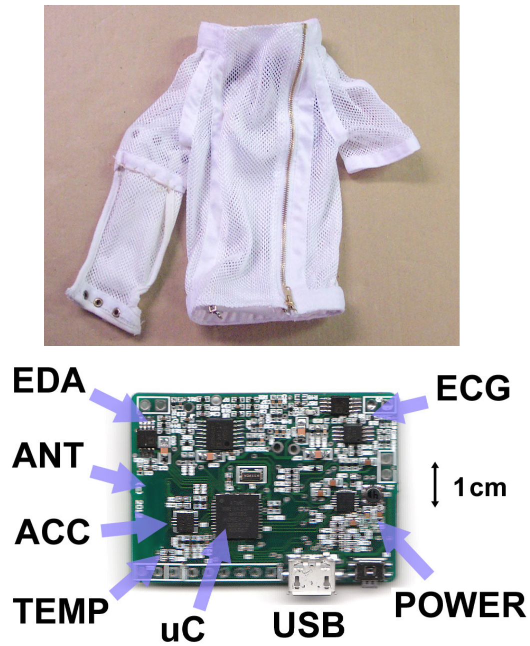

Fig. 1. (top) Monkey vest with sleeve extension; (bottom) top side of sensor circuit board indicating EDA, antenna, accelerometer, temp sensor, ECG and power management. The radio module and micro-SD card are located on the bottom side.

Autonomic nervous system activity, as manifested in psychophysiological parameters such as heart rate variability (HRV) and electrodermal activity (EDA), provides a means to monitor aspects of mood and emotion electronically. Mobile health technologies, such as smart phones and wearable sensors now allow continuous monitoring of these psychophysiological parameters and can be used to deliver personalized therapies as an adjunct to existing mental health treatment [2]. However, the links between neural function and behavior are not yet fully understood and the interpretation of physiological data collected over many hours or many days in a real-world setting represents a major challenge in the context of mental health research and intervention efforts. As a result, there still exists a need for new research tools, methodologies, and outcome measures.

B. Non-Human Primates

The use of non-human primates provides a unique opportunity to study neural function as it relates to

Manuscript received Mar 28, 2012. This work was funded by the Jane Botsford Johnson foundation and NIH /NINDS R01 NS025529
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behavior and environmental and social factors. The hormone oxytocin, for example, has been shown to enhance certain social skills in monkeys and humans and has been used in the treatment of autism [3]. While long-term behavioral studies are logistically difficult in humans, experiments with non-human primates can be performed in highly-controlled settings for prolonged periods of time.

Most animal studies addressing neural function are directed at measuring of neuronal activity, with a long-term vision of creating "neural prostheses" and brain-machine interfaces (BMI) for humans afflicted with brain damage or impairment. While many challenges remain, considerable technical progress has been made in this field, including the capacity for wireless monitoring of neural activity [4]. Since these systems require sensors with microvolt sensitivity and 10 microsecond resolution over many channels, however, the cost and size of this equipment remains out of reach for mobile and personal health systems in the near future.

As a complement to research in neural signaling, the ability to monitor autonomic activity and behavior while controlling for environmental and social factors represents a critical new direction for fundamental research, one with great significance for managing and supporting a variety of mental health disorders. The technology used in research with non-human primates can not only yield insight into the neuronal basis of mental disorders, but, critically, can readily be adapted to emerging human mobile heath technologies that are low-cost and highly scalable.

II. SYSTEM DESCRIPTION AND METHODOLOGY

A. Sensor Module

Recording the physiology of non-human primates poses separate engineering challenges of its own including: choice of measurement site, hairy skin, electrical noise, motion artifacts, portability/size, battery-life, and possible destruction of the sensors by a monitored monkey or by other companion monkeys.

The sensor module unit was implemented using a low-power 8-bit microcontroller (Atmel XMega) with 12-bit ADC resolution for sampling the analog sensors, and a 32 KHz crystal real-time clock. A low-power Bluetooth radio was incorporated into the electronic module to enable communication directly with the mobile phone. All data were locally time-stamped with millisecond precision and synchronized to global time on the phone. A higher-gain ECG circuit adapted for small primates employed a sampling rate of 320 Hz with a discrete wavelet filter for detecting the R peaks and calculating the R-R interbeat intervals. *Instantaneous heart rate* was defined as the reciprocal of this interval, and the *heart rate variability* defined as the SDNN standard deviation of this interval over 10 heart beats and calculated on the smart phone. Data were transmitted at a rate of 4 Hz, adjustable over of a range of 0.1 Hz to 32 Hz via the Bluetooth link, depending on desired battery life and time resolution. The integrated radio data buffer, error checking, and fast protocol provide robust protection against packet loss.

In order to achieve compact size for this application, all of the sensors (ECG, EDA, 3-axis accelerometer, and temperature) were combined into a single circuit board, which we had previously implemented as separate sensor modules [2]. Careful attention was given to the firmware design to implement and synchronize multiple firmware interrupts to service all the events that were taking place simultaneously. In order to provide further reduction in power, the ECG circuit was also redesigned using the INA333 low-power instrumentation amplifier.

For extending recording, a 2GB micro-SD card was integrated into the sensor band, allowing the sensor unit to collect data locally (Bluetooth OFF) without a phone for later retrieval over the wireless Bluetooth connection.

The sensor unit contains a rechargeable 3.7V 650mHA lithium polymer battery and circuitry to support battery recharging via USB. With all sensors ON and Bluetooth connected and continuously transmitting and writing to the SD card at 4Hz, the measured average power consumption was approximately 53 mW with a battery life slightly more than 12 hours. With Bluetooth turned OFF, the battery life was slightly more than 73 hours.

B. Sensor Placement and Packaging

To mount and protect the sensor unit and wire leads, a standard soft mesh monkey vest (made by Lumir) was used [Figure 1]. The sensor electronics module was housed in a 4cm X 4cm X 2cm plastic case and was mounted in a custom pocket on the inside of the monkey vest.

The ECG leads were connected to the monkey's chest with standard adhesive Ag/Ag-Cl electrodes and shielded wire leads. An additional pair of small electrodes was attached to the palm, and a sleeve extension for the monkey vest was used to protect the wire leads.

It should be noted that we have also explored measurement of EDA from the shoulder and chest, which have been shown to be viable alternate measurement sites [5]. Our preliminary data, however, has produced mixed results and is fairly location-dependent. Other locations on the abdomen will be explored further in order to minimize the placement of electrodes on the hands or feet.

C. Mobile Phone Software

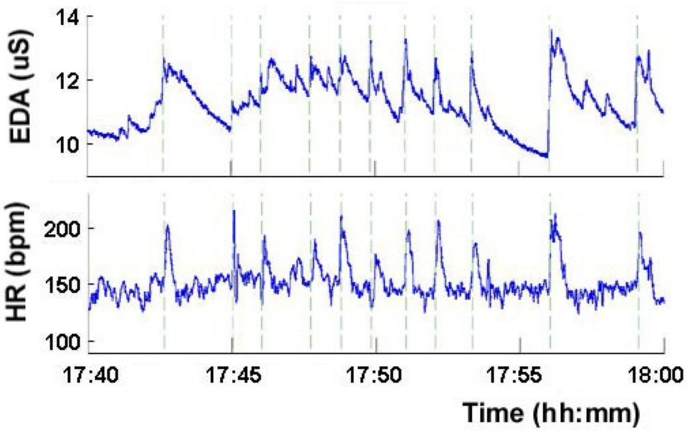

Fig. 2. Electrodermal activity and heart rate response to startle stimulus (air puff). Each vertical dashed line indicates the time a stimulus was applied.

The mobile phone software was implemented with the Android OS and the JAVA SDK. The Google Nexus S phone, running Android 4.0 was used for data collection. The mobile software provides a real-time plot of all measured parameters, with the option to record. The touch screen menu also provides a button for inserting data markers and annotations to indicate specific events. Using the Bluetooth 2.x protocol, up to seven monkeys can be monitored simultaneously.

III. Experiment and Results

A. General Objectives

For testing and evaluation of the sensor platform, controlled experiments were conducted with two adult female rhesus macaque monkeys, with the long-term goal of studying social behavior in an untethered fashion. Each monkey was kept in a large cage shared with another female occupant, and other nearby cages housing neighboring monkeys. Rhesus macaque monkeys are known to develop social bonds with their cage mates, and grooming behavior can be observed between monkeys as a means of regulating social behavior based on gender, age and social rank.

B. Laboratory Data

To illustrate recording of autonomic responses in the laboratory, a standard startle response test was administered by spraying a puff of compressed air to the monkey's face, while the monkey was seated in the chair. As shown in Figure 2, a phasic increase in skin conductance (EDA) and heart rate accompanied each air puff stimulus.

C. Ambulatory Data

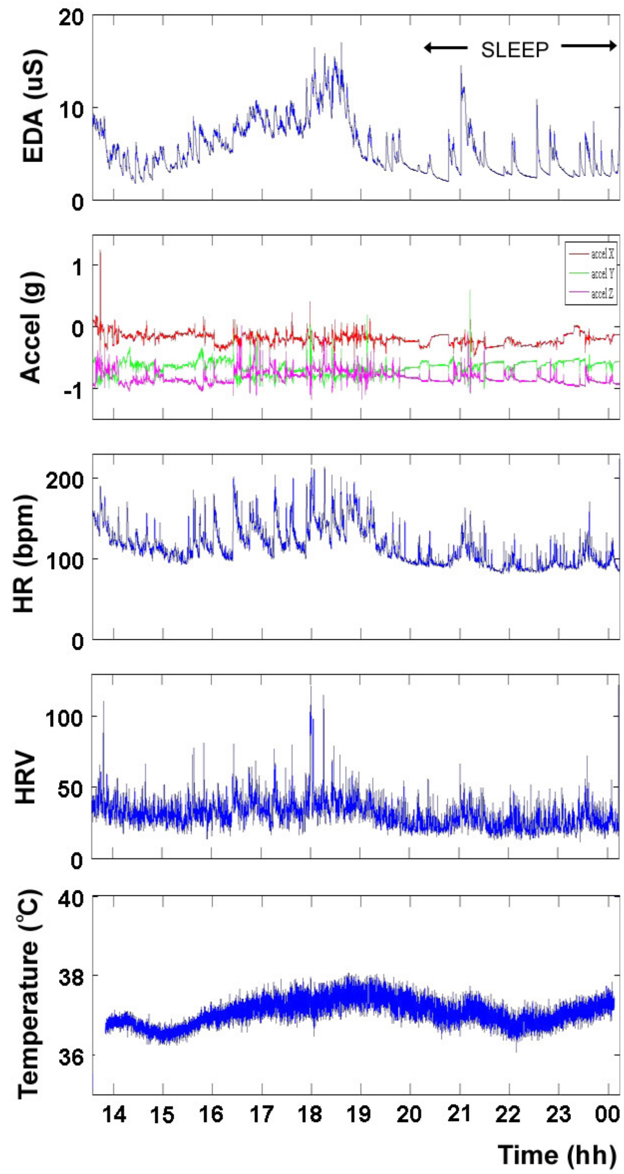

Fig. 3. Sample ambulatory data from rhesus macaque recorded for 11+ hours inside large monkey cage.

Typical laboratory settings with chair-restrained monkeys are most commonly used to test neural function in large primates, but the large cage environment provides an appropriate setting to study social interaction, social cues, and sleep behavior. In our monkey housing facility, the two female monkeys were paired in a single cage, which is common practice to allow the monkeys to develop and to express species-specific and socially-relevant behavioral patterns. In Figure 3, sample physiological data are shown for a span of 11 hours, from approximately 1:30PM to 12:30AM, with the ambient lights turned off at 7PM. During this time, a video camera was also used to record behavior and allow further annotation of the physiological data.

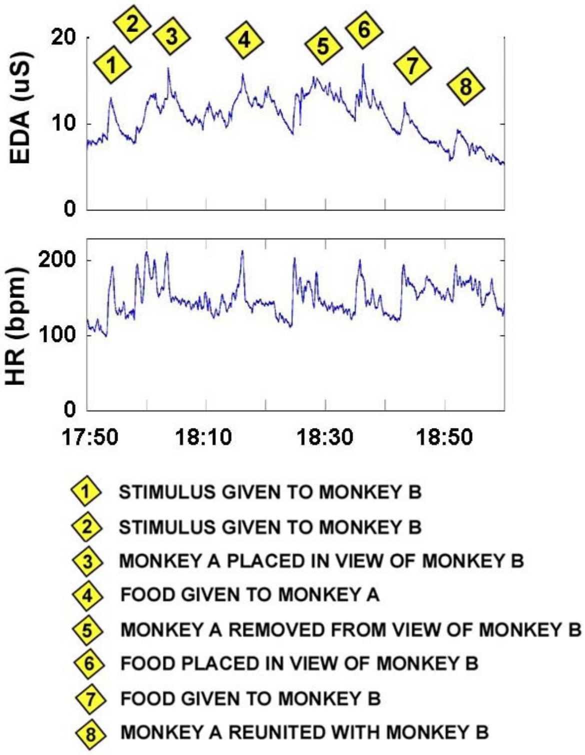

Fig. 4. Sample behavioral data from ambulatory rhesus macaque monkey illustrating the use of the wireless system.

In addition to observing naturally-occurring behavior, the cage environment can be used to study a pair of monkeys and monitor how one monkey reacts to a stimulus applied to the other monkey. In Figure 4, for example, a 70-minute segment of data is shown that demonstrates a simple "envy" or "craving" response. A partition temporarily separated the monkeys and food was given to monkey A only, while physiological data were recorded from monkey B. From the video, we confirmed that monkey B observed monkey A while eating. The sympathetic activation of monkey B was clearly observed.

B. Sleep Data

Yet another application of ambulatory autonomic measurement is the ability to study sleep patterns and circadian rhythms as a function of several factors, such as environmental stress or administration of drugs (e.g. caffeine, opioids). As shown in Figure 3, significant EDA activity is also present during sleep. Although electroencephalography (EEG) measurements are not taken in this case, the EDA signal can be used as an indicator of slow-wave sleep, and has been shown to be a useful probe for monitoring sleeping disorders and circadian rhythm. [7]

IV. Discussion

We have demonstrated effective use of a wireless wearable multi-sensor platform adapted for the purpose of monitoring autonomic activity in non-human primates. The system is highly portable, simple to use, and relatively low-cost and scalable. By making use of a wearable jacket, the units can be easily transferred across monkeys or replicated for monitoring multiple monkeys.

As a research tool, the wireless system is complementary to neural signal monitoring, and enables the use of non-human primates for conducting long-term, highly controlled studies of social behavior that are not practical to do with humans. Of special note, this system allows researchers to investigate behaviors in freely-moving and socially interacting monkeys. By investigating the interplay between social behavior and autonomic activity, our goal is to further understand the neurophysiological basis of a wide range of associated pathologies and disorders ranging from ASD, post-traumatic stress disorder (PTSD), and mood disorders, as well as substance abuse and other addictive behaviors that impact social interaction.

Acknowledgement

We would like to acknowledge Satoko Amemori and Margo Cantor for their enormous assistance with the primate experiments, and Jahui Carrie Liang for assistance with data processing and visualization.

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